AASHTO/AWS D1.5M/D1.5:2020
An American National Standard

Bridge Welding Code

A Joint Publication of

American Association of State Highway and Transportation Officials

AASHTO

American Welding Society®

Approved American National Standard
ANSI

AASHTO/AWS D1.5M/D1.5:2020
An American National Standard

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Bridge Welding Code

8th Edition

Revises AASHTO/AWS D1.5M/D1.5:2015

Prepared by the
American Welding Society (AWS) D1 Committee on Structural Welding
AASHTO Highway Subcommittee on Bridges and Structures

Under the Direction of the
AWS Technical Activities Committee
AASHTO Executive Committee

Approved by the
AWS Board of Directors
AASHTO Board of Directors/Policy Committee

Abstract

This code covers the welding requirements for welded bridges made from carbon and low-alloy constructional steels and designed to AASHTO or AREMA requirements. This 2020 edition contains dimensions in metric SI Units and U.S. Customary Units. Clauses 1 through 9 constitute a body of rules for the regulation of welding in steel construction. Clauses 10 and 11 do not contain provisions, as their analogue D1.1 sections are not applicable to the D1.5 code. Clause 14 contains the requirements for fabricating fracture critical members.

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This standard is subject to revision at any time by the AWS D1 Committee on Structural Welding. It must be reviewed every five years, and if not revised, it must be either reaffirmed or withdrawn. Comments (recommendations, additions, or deletions) and any pertinent data that may be of use in improving this standard are required and should be addressed to AWS Headquarters. Such comments will receive careful consideration by the AWS D1 Committee on Structural Welding and the author of the comments will be informed of the Committee's response to the comments. Guests are invited to attend all meetings of the AWS D1 Committee on Structural Welding to express their comments verbally. Procedures for appeal of an adverse decision concerning all such comments are provided in the Rules of Operation of the Technical Activities Committee. A copy of these Rules can be obtained from the American Welding Society, 8669 NW 36 St, # 130, Miami, FL 33166.

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Foreword

This foreword is not part of this standard but is included for informational purposes only.

The original preparation of this specification was undertaken in response to a need for a common welding specification for the fabrication of steel highway bridges across the country. Prior to its publication, the departments of highways and transportation that make up the American Association of State Highway and Transportation Officials (AASHTO) had routinely used other specifications of the American Welding Society (AWS) Structural Welding Committee, with various unique modifications, to produce contract documents suitable for the construction of bridges. The proliferation of disparate requirements resulted in the need for a single specification that could facilitate uniformity and improved economy in steel bridge fabrication, while at the same time addressing the issues of structural integrity and public safety.

The first AWS code for *Fusion Welding and Gas Cutting in Building Construction* was published in 1928. In 1934, a committee was appointed to prepare specifications for the design, construction, alteration, and repair of highway and railway bridges. The first bridge specification was published in 1936. Until 1963, there were separate AWS committees for bridges and buildings. These two committees joined in 1963 to form the Structural Welding Committee of the American Welding Society. The committee has since promulgated standards for the application of welding to the design and construction of structures.

The Federal Highway Administration of the United States Department of Transportation requires states using federal funds for the construction of welded highway bridges to conform to specified standards for design and construction. Conformance to the AWS *Specification for Welded Highway and Railway Bridges* was first specified in the third edition of the AASHTO *Standard Specifications for Highway Bridges* in 1941. In 1962, the Bureau of Public Roads, now the Federal Highway Administration (FHWA), required conformance to a Circular Memorandum, dated November 13, 1962, which transmitted additional provisions for welding A36 steel pending publication of an AWS specification which would contain certain essential provisions not then in the code. Another Circular Memorandum, dated February 11, 1965, specified requirements for CVN testing, and a further Circular Memorandum, dated August 19, 1966, modified provisions of the 1966 Edition of AWS D2.0-66, *Specification for Welded Highway and Railway Bridges*.

In 1974, AASHTO published the first edition of the *Standard Specification for Welding of Structural Steel Highway Bridges*. The Eleventh Edition of the AASHTO *Standard Specifications for Highway Bridges*, dated 1977, directed "Welding shall conform to the requirements of the AASHTO *Standard Specifications for Welding of Structural Steel Highway Bridges* 1974 and subsequent interim specifications . . ." AASHTO published the Second and Third editions of the *Standard Specifications for Welding of Structural Steel Highway Bridges* in 1977 and 1981. All of the AASHTO specifications were required to be part of the Contract Documents as modifications or additions to the AWS *Structural Welding Code—Steel.* This was a cumbersome procedure.

In 1982, a subcommittee was formed jointly by AASHTO and AWS, with equal representation from both organizations, to seek accommodation between the separate and distinct requirements of bridge owners and existing provisions of AWS D1.1. The *Bridge Welding Code* is the result of an agreement between AASHTO and AWS to produce a joint AASHTO/AWS *Bridge Welding Code* for steel bridges that addresses essential AASHTO needs and makes AASHTO revisions mandatory.

The first edition of the *Bridge Welding Code*, published in 1988, provided for the qualification of welding procedures by test to assure that welds have the strength, ductility, and toughness necessary for use in redundant structures. Nonredundant fracture critical bridge members were not provided for in the first edition of the code. While qualification of welding procedures is required, a major effort has been made to specify the minimum number of tests and the simplest tests that give reasonable assurance of required mechanical properties. Efforts are made to discourage individual States from requiring duplication of weld testing unless that testing is specified in the bid documents. Special attention is directed to avoidance of unnecessary hardening of base metal HAZs and the avoidance of hydrogen and other items that can lead to weld or base-metal cracking.

Consequently, while the D1.5-88 document has a superficial resemblance to D1.1 in its general format, there are significant differences that users should be aware of, among them the lack of provisions relating to statically loaded structures, tubular construction or the modification of existing structures. Users are encouraged to develop their own requirements for these applications or use existing documents (e.g., D1.1) with the appropriate modifications.

Changes in Code Requirements. Underlined text in the clauses, subclauses, tables, figures, or forms indicates a change from the 2015 edition. A vertical line in the margin of a table or figure also indicates a change from the 2015 edition.

The publication of AASHTO/AWS D1.5M/D1.5:2020 was justified by the need to monitor, revise, and update code provisions based on the needs of AASHTO member states and industry. The following is a list of the most significant revisions in the 2020 edition:

Summary of Changes

Clause/Table/Figure/Annex	Modification
Clause 1	Revisions were made to the approved base metals and grades.
Clause 2	This is a new clause listing normative references. It replaces Annex P from the previous edition.
Clause 3	This is a new clause that provides terms and definitions specific to this standard. It replaces Annex D from the previous edition. New definitions were added.
Clause 4	Clause 4 was presented as Clause 2 in the previous edition. Revisions were made to the symbols (S) and (E) for alignment with AWS A2.4.
Clause 5	Clause 5 was presented as Clause 3 in the previous edition. Revisions were made to base metal cleanliness, tack welds, chipping and brushing language, assembly, and dimensional tolerances. Instances of “grind” or “mill” were changed to “finish”.
Clause 6	Clause 6 was presented as Clause 4 in the previous edition. Revisions were made to FC provisions. Instances of “grind” or “mill” were changed to “finish”.
Clause 7	Clause 7 was presented as Clause 5 in the previous edition. Revisions were made to the renaming of electrodes, and mismatch qualification. New tables, 7.1 and 7.2, were added.
Clause 8	Clause 8 was presented as Clause 6 in the previous edition. Revisions were made to nondestructive testing, flaw and discontinuity language, digital radiography, and QA/QC language. Instances of “grind” or “mill” were changed to “finish”. New table, 8.1 was added. Table 8.3 was updated for backgouging. Clause 8 from the 2015 edition was deleted.
Clause 9	Clause 9 was presented as Clause 7 in the previous edition. Revisions were made to failed stud repairs. Clause 9 from the 2015 edition was deleted.
Clause 10	No changes were made to Clause 10.
Clause 11	No changes were made to Clause 11.
Clause 12	Revisions were made to sole plates and fracture critical criteria. New table, 12.2, was added.
Annex A	
Annex B	
Annex C	
Annex D	Annex D was presented as Annex E in the previous edition.
Annex E	Annex E was presented as Annex F in the previous edition.
Annex F	Annex F was presented as Annex G in the previous edition.
Annex G	Annex G was presented as Annex H in the previous edition.
Annex H	Annex H was presented as Annex I in the previous edition.
Annex I	Annex I was presented as Annex J in the previous edition.
Annex J	Annex J was presented as Annex K in the previous edition. Revisions were made to flaw and discontinuity language, personnel requirements, and the testing of welds.
Annex K	Annex K was presented as Annex L in the previous edition.
Annex L	Annex L was presented as Annex M in the previous edition. Revisions were made to flaw and discontinuity language.
Annex M	Annex M was presented as Annex N in the previous edition.

(Continued)

Summary of Changes (Continued)

Clause/Table/Figure/Annex	Modification
Annex N	Annex N was presented as Annex O in the previous edition.
Annex O	Annex O was presented as Annex Q in the previous edition. Annex P from the previous edition was deleted.
Annex P	Annex P was presented as Annex R in the previous edition.
Commentary	Revisions were made to numbering due to the movement of clauses and annexes, addition of text, deletion of text, and addition of new tables and figures.

Commentary. The Commentary is nonmandatory and is intended only to provide insightful information into provision rationale.

Normative Annexes. These annexes address specific subjects in the code and their requirements are mandatory requirements that supplement the code provisions.

Informative Annexes. These annexes are not code requirements but are provided to clarify code provisions by showing examples, providing information, or suggesting alternative good practices.

Index. As in previous codes, the entries in the Index are referred to by subclause number rather than by page number. This should enable the user of the Index to locate a particular item of interest in minimum time.

Errata. It is the Structural Welding Committee's Policy that all errata should be made available to users of the code. Therefore, any significant errata will be published in the Society News Section of the *Welding Journal* and posted on the AWS web site at: http://www.aws.org/technical/d1/.

Suggestions. Your comments for improving AWS D1.5M/D1.5:2015, *Bridge Welding Code* are welcome. Submit comments to the Managing Director, Standards Development Division, American Welding Society, 8669 NW 36 St, # 130, Miami, FL 33166; telephone (305) 443-9353; fax (305) 443-5951; e-mail info@aws.org; or via the AWS web site <http://www.aws.org>.

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Bridge Welding Code

1. General Provisions

1.1 Application

1.1.1 This code covers welding fabrication requirements applicable to welded highway bridges. The code is applicable to both shop and field fabrication of steel bridges and bridge components. The code is to be used in conjunction with the AASHTO *Standard Specification for Highway Bridges* or the AASHTO *LRFD Bridge Design Specifications*.

The code is not intended to be used for the following:

(1) Steels with a minimum specified yield strength greater than 690 MPa [100 ksi]

(2) Pressure vessels or pressure piping

(3) Base metals other than carbon or low-alloy steels

(4) Structures composed of structural tubing

Fabrication of structures or components not specifically addressed by this code shall be performed in conformance with the special provisions of the contract or in conformance with the written directives of the Engineer who may choose to reference an alternate applicable welding standard.

1.1.2 The fundamental premise of the code is to provide general stipulations applicable to any routine bridge situation. Acceptance criteria for production welds different from those described in the code may be used for a particular application, provided they are suitably documented by the proposer and approved by the Engineer.

Such alternate acceptance criteria may be based on the evaluation of suitability for service using past experience, experimental evidence, or engineering analysis considering material type, service load effects, and environmental factors.

1.1.3 The term *Engineer* as used in this code shall mean the State Bridge Engineer, or the Bridge Engineer's designated representative. The Engineer acts on behalf of the State or Owner and unless otherwise specified, shall be the Owner's official representative. All references to acceptance or approval shall mean acceptance or approval by the Engineer.

1.1.4 The term *Contractor* as used in this code indicates the party responsible for performing the work as required by the contract documents. The term Contractor is used collectively to mean contractor, manufacturer, fabricator, erector, or other party performing the work.

1.2 Base Metal

1.2.1 Specified Base Metal. The contract documents shall designate the specification and classification of base metals to be used.

1.2.2 Approved Base Metals. Base metals to be welded under this code shall meet the requirements of the latest edition of AASHTO M 270M/M 270 (ASTM A709/A709M) for the following grades:

(1) 250 [36],

(2) 345 [50] (Type 1, 2, or 3),

(3) 345S [50S],

(4) 345W [50W],

(5) HPS 345W [HPS 50W],

(6) HPS 485W [HPS 70W], or

(7) HPS 690W [HPS 100W]

1.2.3 Thickness Limitations. The provisions of this code do not apply to welding base metals less than 3 mm [1/8 in] thick. Where base metals thinner than 3 mm [1/8 in] are to be welded, the requirements of AWS D1.3/D1.3M, *Structural Welding Code—Sheet Steel*, should apply. When used in conjunction with AWS D1.3/D1.3M, the applicable provisions of this code shall be observed.

1.3 Welding Processes

1.3.1 This code addresses SMAW, SAW, FCAW, GMAW, ESW, EGW, and SW. Other welding processes may be used if approved by the Engineer. These processes shall be qualified by the applicable tests described in 7.12.4 and any other tests required by the Engineer. In conjunction with the tests, the WPSs and limitations of essential variables applicable to the specific welding process shall be established by the Contractor developing the WPS. The ranges of essential variables shall be based on documented evidence of experience with the process, or a series of tests shall be conducted to establish the limits of variables. Any change to an essential variable outside the established range shall require requalification.

1.3.2 Shielded metal arc welding (SMAW) WPSs (Welding Procedure Specifications) that conform to the provisions of Clauses 4, 5, and 6, are operated within the limitation of variables recommended by the manufacturer, and that produce weld metal with a minimum specified yield strength less than 620 MPa [90 ksi], shall be deemed prequalified and exempt from the tests described in Clause 7. WPSs for SAW, FCAW, GMAW, ESW, and EGW shall be qualified as described in 7.12, as applicable.

1.3.3 Electrogas (EGW) welding may be used for groove welds in butt joints in compression, provided the WPSs conform to the applicable provisions of Clauses 4, 5, and 6, and are qualified in accordance with the requirements of 7.13. EGW shall be subject to nondestructive testing, as specified in Clause 8.

1.3.4 Electroslag (ESW) may be used for Zone I and II non-fracture-critical bridge members and member components, including components subject to tensile stresses or reversal of stress, provided the WPSs conform to the applicable provisions of Clauses 4, 5, and 6, and are qualified in accordance with the requirements of 7.14. ESW shall be subject to nondestructive testing, as specified in Clause 8. Only the "narrow-gap improved" ESW process (ESW-NG) shall be permitted, unless another process is approved in accordance with Annex I. Application of ESW shall be limited to members or member components made from M 270M/M 270 (A709/A709M) Grades 250 [36], 345 [50], 345S [50S], and 345W [50W] steels.

1.3.5 Stud welding may be used, provided the WPSs conform to the applicable provisions of Clause 9.

1.3.6 GMAW-S (short circuit arc) is not recommended for the construction of bridge members and shall not be permitted without written approval of the Engineer.

1.3.7 Welding of Ancillary Products. Unless otherwise provided in the contract documents, ancillary products, such as drainage components, expansion dams, curb plates, bearings, hand rails, cofferdams, sheet piling, and other products not subject to calculated tensile stress from live load and not welded to main members in tension areas as determined by the Engineer, may be fabricated without performing the WPS qualification tests described in Clause 7, subject to the following restrictions:

(1) SMAW, SAW, FCAW, and GMAW WPSs shall be considered prequalified and exempt from the qualification tests described in Clause 7, provided that welding is performed in conformance with all other provisions of the code.

(2) All welding performed in conformance with this subclause shall be conducted within the limitations of welding variables recommended by the filler metal manufacturer. Welds attaching ancillary products to main members shall meet all requirements of the code, including WPS qualification testing.

(3) The Engineer shall be the final judge of which products are considered ancillary and exempt from qualification tests.

1.4 Fabricator Requirements

Fabricators shall be certified under the AISC Quality Certification Program, Simple Steel Bridges, Intermediate Steel Bridges, or Complex Steel Bridges as required by the Engineer, or an equivalent program acceptable to the Engineer.

1.5 Definitions

The welding terms used in this code shall be interpreted in conformance with the definitions given in the latest edition of AWS A3.0, *Standard Welding Terms and Definitions, Including Terms for Adhesive Bonding, Brazing, Soldering, Thermal Cutting, and Thermal Spraying*, supplemented by Clause 3 of this code.

1.6 Welding Symbols

Welding symbols shall be those shown in AWS A2.4, *Standard Symbols for Welding, Brazing, and Non-destructive Examination*. Special conditions shall be fully explained by notes or details.

1.7 Safety Precautions

Safety and health issues and concerns are beyond the scope of this standard and therefore are not addressed herein. Safety and health information is available from the following sources:

American Welding Society:

(1) ANSI Z49.1, Safety in Welding, Cutting, and Allied Processes

(2) AWS Safety and Health Fact Sheets

(3) Other safety and health information on the AWS website

Material or Equipment Manufacturers:

(1) Safety Data Sheets supplied by materials manufacturers

(2) Operating Manuals supplied by equipment manufacturers

Applicable Regulatory Agencies

Work performed in accordance with this standard may involve the use of materials that have been deemed hazardous, and may involve operations or equipment that may cause injury or death. This standard does not purport to address all safety and health risks that may be encountered. The user of this standard should establish an appropriate safety program to address such risks as well as to meet applicable regulatory requirements. ANSI Z49.1 should be considered when developing the safety program.

1.8 Standard Units of Measurement

This standard makes use of both the International System of Units (SI) and U.S. Customary Units. The latter are shown within brackets ([ ]) or in appropriate columns in tables and figures. The measurements may not be exact equivalents; therefore each system must be used independently.

1.9 Welding Procedure Specifications (WPSs)

All production welding shall be performed in conformance with the provisions of an approved Welding Procedure Specification (WPS), which is based upon successful test results as recorded in a Procedure Qualification Record (PQR) unless qualified in conformance with 1.3.2. All WPSs shall reference the PQR that is the basis for acceptance. A copy of the proposed WPS and referenced PQR shall be submitted to the Engineer for approval. Recommended forms for WPSs and PQRs are provided in Annex N. WPSs for SMAW that meet the requirements of 7.11 shall be considered prequalified and exempt from qualification testing.

1.10 Mechanical Testing

The latest edition of AWS B4.0 or B4.0M, *Standard Methods for Mechanical Testing of Welds*, provides additional details of test specimen preparation and details of test fixture construction.

1.11 Reference Documents

See Clause 2 for a description of the documents referenced in AASHTO/AWS D1.5M/D1.5:2020

2. Normative References

The documents listed below are referenced within this publication and are mandatory to the extent specified herein. For undated references, the latest edition of the referenced standard shall apply. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply.

American Association of State Highway and Transportation Officials (AASHTO) documents:[1]

AASHTO Guide Specifications for Highway Bridge Fabrication with HPS 70W (HPS 485W) Steel

AASHTO Standard Specification for Highway Bridges

AASHTO LRFD Bridge Design Specifications

AASHTO M270M/M270, *Standard Specification for Structural Steel Bridges*

AASHTO T244, *Standard Method of Test for Mechanical Testing of Steel Products*

American Welding Society (AWS) documents:[2]

AWS A2.4, *Symbols for Welding, Brazing, and Nondestructive Examination*

AWS A3.0, *Standard Welding Terms and Definitions, Including Terms for Adhesive Bonding, Brazing, Soldering, Thermal Cutting, and Thermal Spraying.*

AWS A4.3, *Standard Methods for Determination of the Diffusible Hydrogen Content of Martensitic, Bainitic, and Ferritic Steel Weld Metal Produced by Arc Welding*

A4.4M, *Standard Procedures for Determination of Moisture Content of Welding Fluxes and Welding Electrode Flux Coverings*

AWS A5.01M/A5.01:2013 (ISO 14344:2010 MOD) *Welding Consumables – Procurement of Filler Metals and Fluxes*

AWS A5.1/A5.1M, *Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding*

AWS A5.5/A5.5M, *Specification for Low-Alloy Steel Electrodes for Shielded Metal Arc Welding*

AWS A5.17/A5.17M, *Specification for Carbon Steel Electrodes and Fluxes for Submerged Arc Welding*

AWS A5.18/A5.18M, *Specification for Carbon Steel Electrodes and Rods for Gas Shielded Arc Welding*

AWS A5.20/A5.20M, *Specification for Carbon Steel Electrodes for Flux Cored Arc Welding*

AWS A5.23/A5.23M, *Specification for Low-Alloy Steel Electrodes and Fluxes for Submerged Arc Welding*

AWS A5.25/A5.25M, *Specification for Carbon and Low-Alloy Steel Electrodes and Fluxes for Electroslag Welding*

AWS A5.26/A5.26M, *Specifications for Carbon and Low-Alloy Steel Electrodes for Electrogas Welding*

AWS A5.28/A5.28M, *Specification for Low-Alloy Steel Electrodes and Rods for Gas Shielded Arc Welding*

AWS A5.29/A5.29M, *Specification for Low-Alloy Steel Electrodes for Flux Cored Arc Welding*

AWS B4.0, *Standard Methods for Mechanical Testing of Welds*

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[1] AASHTO documents are published by the American Association of State Highway and Transportation Officials, 444 N. Capitol Street NW, Suite 249, Washington DC 20001.
[2] AWS documents are published by the American Welding Society, 8669 NW 36th Street, #130, Miami, FL 33166.

AWS C4.1-G, *Oxygen Cutting Surface Roughness Gauge*

AWS C5.4, *Recommended Practices for Stud Welding*

AWS D1.1/D1.1M, *Structural Welding Code—Steel*

AWS D1.3/D1.3M, *Structural Welding Code—Sheet Steel*

AWS QC1, *Standard for AWS Certification of Welding Inspectors*

AWS *Welding Handbook,* Volume 1, 8th Edition, Chapter 11

American National Standards Institute (ANSI) document:[3]

ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*

American Society of Mechanical Engineers (ASME) documents:[4]

ASME B46.1, *Surface Texture (Surface Roughness, Waviness, and Lay)*

ASME *Boiler and Pressure Vessel Code*, Section V, Article 2

American Society for Nondestructive Testing (ASNT) document:[5]

ASNT *Recommended Practice No.* SNT-TC-1A, *Personnel Qualification and Certification in Nondestructive Testing*

ASTM International (ASTM) documents:[6]

ASTM A6/A6M, *Standard Specification for General Requirements for Rolled Structural Steel Bars, Plates, Shapes, and Sheet Piling*

ASTM A108, *Standard Specification for Steel Bar, Carbon, and Alloy, Cold-Finished*

ASTM A370, *Standard Test Methods and Definitions for Mechanical Testing of Steel Products*

ASTM A435/A435M, *Standard Specification for Straight-Beam Ultrasonic Examination of Steel Plates*

ASTM A709/A709M, *Standard Specification for Structural Steel Bridges*

ASTM A770/A770M, *Standard Specification for Through-Thickness Tension Testing of Steel Plates for Special Applications*

ASTM E23, *Standard Methods for Notched Bar Impact Testing of Metallic Materials*

ASTM E94, *Standard Guide for Radiographic Examination*

ASTM E140, *Standard Hardness Conversion Tables for Metals*

ASTM E164, *Standard Practice for Contact Ultrasonic Testing of Weldments*

ASTM E165, *Standard Practice for Liquid Penetrant Examination for General Industry*

ASTM E317, *Standard Practice for Evaluating Performance Characterstics of Ultrasonic Pulse-Echo Testing Instruments and Systems without the Use of Electronic Measurement Instruments*

ASTM E384, *Standard Test Method for Knoop and Vickers Hardness of Materials*

ASTM E709, *Standard Guide for Magnetic Particle Testing*

ASTM E747, *Standard Practice for Design, Manufacture, and Material Grouping Classification of Wire Image Quality Indicators (IQI) Used for Radiology*

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[3] This ANSI document is published by the American Welding Society, 8669 NW 36th Street, #130, Miami, FL 33166.
[4] ASME documents are published by the American Society of Mechanical Engineers, Two Park Avenue, New York, NY 10016-5990.
[5] This ASNT document is published by the American Society for Nondestructive Testing, P.O. Box 28518, 1711 Arlingate Lane, Columbus, OH 43228-0518.
[6] ASTM International documents are published by ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.

ASTM E1025, *Standard Practice for Design, Manufacture, and Material Grouping Classification of Hole-Type Image Quality Indicators (IQI) Used for Radiography*

ASTM E1032, *Standard Test Method for Radiographic Examination of Weldments*

ASTM E1254, *Standard Guide for Storage of Radiographs and Unexposed Industrial Radiographic Films*

ASTM E2033, *Standard Practice for Computed Radiology (Photostimulable Luminescence Method)*

ASTM E2339, *Digital Imaging and Communication in Nondestructive Evaluation (DICONDE)*

ASTM E2445, *Standard Practice for Qualification and Long-Term Stability of Computed Radiology Systems*

ASTM E2698, *Standard Practice for Radiological Examination Using Digital Detector Arrays*

ASTM E2699, *Standard Practice for Digital Imaging and Communication in Nondestructive Evaluation (DICONDE) for Digital Radiographic (DR) Test Methods.*

ASTM E2737, *Standard Practice for Digital Detector Array Performance Evaluation and Long-Term Stability*

CSA Group (CSA) document:[7]

Canadian Standard Association (CSA) Standard W178.2, *Certification of Welding Inspectors*

International Institute of Welding (IIW) document:[8]

The International Institute of Welding (IIW) Ultrasonic Reference Block

Other documents:

Fracture and Fatigue Control in Structures—Applications of Fracture Mechanics, Barsom and Rolfe, Prentice-Hall Inc. SSC-383, “Optimum Weld-Metal Strength for High Strength Ship Structures”, Dexter and Ferrell, Ship Structure Committee, 1995.[9]

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[7] This CSA document is published by the CSA Group, 178 Rexdale Boulevard, Toronto, ON, CANADA M9W 1R3.
[8] This IIW document is published by the International Institute of Welding, BP 51362 – Villepinte, 95 942 Roissy Ch de Gaulle Cedex, FRANCE.
[9] This SSC document is published by the Ship Structure Committee, <www.shipstructure.org>.

3. Terms and Definitions

The welding terms used in this code shall be interpreted in conformance with the definitions given in the latest edition of AWS A3.0, *Standard Welding Terms and Definitions, Including Terms for Adhesive Bonding, Brazing, Soldering, Thermal Cutting, and Thermal Spraying*.

The terms and definitions in this glossary are divided into two categories: (1) terms, defined by the AWS Structural Welding Committee, that apply only to ultrasonic testing, designated by (UT) following the term, and (2) other terms, preceded by asterisks, that are defined as they relate to this code.

For the purposes of this document, the following terms and definitions apply:

A

***active flux (SAW).** A flux which contains small amounts of manganese or silicon, or both, added to improve the weld in certain single-pass applications. Change in arc voltage or the number of weld passes may significantly change weld metal chemical composition and mechanical properties.

***alloy flux (SAW).** A flux which contains alloy ingredients intended to modify the weld metal chemical composition. Changes in arc voltage may significantly change weld metal chemical composition.

***all-weld-metal test specimen.** A test specimen with the reduced section composed wholly of weld metal.

amplitude length rejection level (UT). The maximum length of discontinuity allowed by various indication ratings associated with weld size, as indicated in Tables 8.4 and 8.5.

attenuation (UT). The loss in acoustic energy which occurs between any two points of travel. This loss may be due to absorption, reflection, etc. (In this code, using the shear wave pulse-echo method of testing, the attenuation factor is 2 dB per 25 mm [1 in] of sound path distance after the first 25 mm [1 in].)

arc gouging. Thermal gouging that uses an arc cutting process variation used to form a bevel or groove.

as-welded. Pertaining to the condition of weld metal, welded joints, and weldments after welding, but prior to any subsequent thermal, mechanical, or chemical treatments.

attenuation (UT). The loss in acoustic energy which occurs between any two points of travel. This loss may be due to absorption, reflection, etc. (In this code, using the shear wave pulse-echo method of testing, the attenuation factor is 2 dB per 25 mm [1 in] of sound path distance after the first 25 mm [1 in].)

automatic welding. Welding with equipment that requires only occasional or no observation of the welding and no manual adjustment of the equipment controls. See also **mechanized welding**.

B

backgouging. The removal of weld metal and base metal from the weld root side of a welded joint to facilitate complete fusion and CJP upon subsequent welding from that side.

backing. A material or device placed against the back side of the joint, or at both sides of a weld in ESW and EGW, to support and retain molten weld metal. The material may be partially fused or remain unfused during welding and may be either metal or nonmetal.

backing pass. A weld pass made for a backing weld.

backing ring. Backing in the form of a ring, generally used in the welding of pipe.

backing weld. Backing in the form of a weld.

back weld. A weld made at the back of a single-groove weld.

base metal. The metal or alloy to be welded, brazed, soldered, or cut.

bevel angle. The angle between the bevel of a joint member and a plane perpendicular to the surface of the member.

blooming pixel. A pixel whose charge spreads to adjacent pixels.

boxing. The continuation of a fillet weld around a corner of a member as an extension of the principal weld.

butt joint. A joint between two members aligned approximately in the same plane.

butt weld. A nonstandard term for a weld in a butt joint. See **butt joint**.

C

***caulking.** Plastic deformation of weld and base metal surfaces by mechanical means to seal or obscure discontinuities.

CJP (complete joint penetration). A joint root condition in a groove weld in which weld metal extends through the joint thickness.

***CJP (complete joint penetration) groove weld.** A groove weld which has been made from both sides or from one side on a backing having complete penetration and fusion of weld and base metal throughout the depth of the joint.

complete fusion. Fusion over the entire fusion faces and between all adjoining weld beads.

computed radiography (CR). A digital replacement of conventional X-ray film that uses a flexible phosphor imaging plate to capture digital images.

***consumable guide ESW or EGW.** An electroslag or electrogas welding process variation in which filler metal is supplied by an electrode(s) and the guiding member(s).

continuous weld. A weld that extends continuously from one end of a joint to the other. Where the joint is essentially circular, it extends completely around the joint.

corner joint. A joint between two members located approximately at right angles to each other.

crater. A depression in the weld face at the termination of a weld bead.

CVN. Charpy V-notch.

D

decibel (dB) (UT). The logarithmic expression of a ratio of two amplitudes or intensities of acoustic energy.

decibel rating (UT). See preferred term **indication rating**.

defect. A discontinuity or discontinuities that by nature or accumulated effect (for example, total crack length) render a part or product unable to meet minimum applicable acceptance standards or specifications. This term designates rejectability.

***defective weld.** A weld containing one or more defects.

defect level (UT). See preferred term **indication rating**.

defect rating (UT). See preferred term **indication rating**.

depth of fusion. The distance that fusion extends into the base metal or previous bead from the surface melted during welding.

discontinuity. An interruption of the typical structure of a material, such as a lack of homogeneity in its mechanical, metallurgical, or physical characteristics. A discontinuity is not necessarily a defect.

downhand. See preferred term **flat welding position**.

***drawings.** As used in this code, refers to plans, design, detail drawings and erection plans.

E

***effective length of weld.** The length throughout which the correctly proportioned cross section of the weld exists. In a curved weld, it shall be measured along the weld axis.

EGW (electrogas welding). An arc welding process that uses an arc between a continuous filler metal electrode, and the weld pool, employing approximately vertical welding progression with backing to confine the molten weld metal. The process is used with or without an externally supplied shielding gas and without the application of pressure.

ESW (electroslag welding). A welding process that produces coalescence of metals with molten slag that melts the filler metal and the surfaces of the workpieces. The weld pool is shielded by this slag which moves along the full cross section of the joint as welding progresses. The process is initiated by an arc that heats the slag. The arc is then extinguished by the conductive slag, which is kept molten by its resistance to electric current passing between the electrode and the workpieces.

The narrow-gap improved electroslag welding process is a version of consumable guide ESW that meets the toughness requirements of AASHTO Temperature Zone 1 and 2 bridges. Compared to conventional electroslag welding, the ESW-NG process is characterized by: (a) improved CVN toughness of the weld metal and heat-affected zone (HAZ), (b) higher fatigue resistance, and (c) increased productivity.

F

faying surface. The mating surface of a member that is in contact with or in close proximity to another member to which it is to be joined.

FCAW (flux cored arc welding). An arc welding process that uses an arc between a continuous filler metal electrode and the weld pool. The process is used with shielding gas from a flux contained within the tubular electrode with or without additional shielding from an externally supplied gas, and without the application of pressure.

filler metal. The metal or alloy to be added in making a welded, brazed, or soldered joint.

fillet weld leg. The distance from the joint root to the toe of the fillet weld.

finish. *verb.* The use of mechanical methods (e.g., grinding, machining) to prepare a surface to meet a quality standard requirement.

***flash.** The material which is expelled or squeezed out around the base of a stud weld.

***flat welding position.** The welding position used to weld from the upper side of the joint when the face of the weld is approximately horizontal.

***flux.** A material used to hinder or prevent the formation of oxides and other undesirable substances in molten metal and on solid metal surfaces, and to dissolve or otherwise facilitate the removal of such substances. See also **active flux** and **neutral flux**.

fusion. The melting together of filler metal and base metal or of base metal only, to produce a weld. See also **depth of fusion**.

***fusion-type discontinuity.** Signifies slag inclusion, incomplete fusion, incomplete joint penetration, and similar discontinuities associated with fusion.

fusion zone. The area of base metal melted as determined on the cross section of a weld.

G

***gas pocket.** A cavity caused by entrapped gas.

GMAW (gas metal arc welding). An arc welding process that uses an arc between a continuous filler metal electrode and the weld pool. The process is used with shielding from an externally supplied gas and without the application of pressure.

***GMAW-S (gas metal arc welding short circuit arc).** A gas metal arc welding process variation in which the consumable electrode is deposited during repeated short circuits.

***gouging (thermal).** The forming of a bevel or groove by material removal. See also **backgouging**, **arc gouging**, and **oxygen gouging**.

groove angle. The total included angle of the groove between workpieces.

groove face. That surface of a joint member included in the groove.

groove weld. A weld made in a groove between the workpieces.

H

HAZ (heat-affected zone). That portion of the base metal with mechanical properties or microstructure that have been altered by the heat of welding, brazing, soldering, or thermal cutting.

***horizontal welding position**

fillet weld. The position in which welding is performed on the upper side of an approximately horizontal surface and against an approximately vertical surface [see Figures 7.4 and 7.7(B)].

groove weld. The position of welding in which the weld axis lies in an approximately horizontal plane and the weld face lies in an approximately vertical plane [see Figures 7.5 and 7.6(B)].

horizontal reference line (UT). A horizontal line near the center of the ultrasonic test instrument scope to which all echoes are adjusted for dB reading.

***hybrid joint.** A welded joint of material with two different minimum specified yield strengths.

hydrogen diffusion postheat. A thermal treatment applied to an assembly after welding for the purpose of releasing diffusible hydrogen.

I

indication (UT). The signal displayed on the test equipment signifying the presence of a sound wave reflector in the part being tested.

indication level (UT). The calibrated gain or attenuation control reading obtained for a reference line height indication from a discontinuity.

indication rating (UT). The decibel reading in relation to the zero reference level after having been corrected for sound attenuation.

intermittent weld. A weld in which the continuity is broken by recurring unwelded spaces.

***interpass temperature (welding).** In a multiple-pass weld, the temperature of the weld before the next pass is started.

***IQI (image quality indicator).** A device whose image in a radiograph is used to determine radiographic quality level. It is not intended for use in judging the size nor for establishing acceptance limits of discontinuities.

J

joint. The junction of members or the edges of members that are to be joined or have been joined.

joint penetration. The distance the weld metal extends from the weld face into a joint, exclusive of reinforcement.

joint root. That portion of a joint to be welded where the members approach closest to each other. In cross section, the joint root may be either a point, a line, or an area.

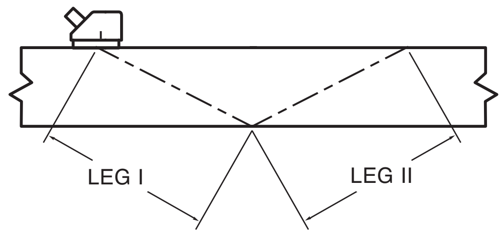
***joint welding procedure.** The materials and detailed methods and practices employed in the welding of a particular joint.

L

lap joint. A joint between two overlapping members in parallel planes.

***layer.** A stratum of weld metal or surfacing material. The layer may consist of one or more weld beads laid side by side.

leg (UT). The path the shear wave travels in a straight line before being reflected by the opposite surface of material being tested. See sketch below for leg identification. *Note: Leg I plus leg II equals one V-path.*



leg of a fillet weld. See **fillet weld leg**.

M

***machine.** *verb.* To shape, plane, mill, grind, cut, rout, abrade or otherwise achieve a desired contour or finish by machine-operated tools.

manual welding. Welding with the torch, gun, or electrode holder held and manipulated by hand. Accessory equipment, such as part motion devices and manually controlled filler material feeders may be used. See **automatic welding**, **mechanized welding**, and **semiautomatic welding**.

***mechanized welding.** Welding with equipment which performs the welding operation under the constant observation and control of a welding operator. The equipment may or may not load and unload the workpieces. See also **automatic welding**.

MT. Magnetic particle testing.

N

neutral flux (SAW). A flux that will not cause a significant change in the weld metal composition when there is a large change in the arc voltage.

node (UT). See preferred term **leg**.

nondestructive testing (NDT). The process of determining acceptability of a material or a component in accordance with established criteria without impairing its future usefulness.

O

***overhead welding position.** The position in which welding is performed from the underside of the joint [see Figures 7.4, 7.5, 7.6(D), and 7.7(D)].

***overlap (fusion welding).** The protrusion of weld metal beyond the weld toe or weld root.

oxygen cutting (OC). A nonstandard term for oxyfuel gas cutting.

oxygen gouging. Thermal gouging that uses an oxygen cutting process variation to form a bevel or groove.

P

***parallel electrode.** See **SAW**.

pass. See preferred term **weld pass**.

peening. The mechanical working of metals using impact blows.

***piping porosity (ESW and EGW).** Elongated gas pores whose major dimension lie in a direction approximately parallel to the weld axis which is vertical during welding.

***piping porosity (general).** Elongated porosity whose major dimension lies in a direction approximately normal to the weld surface. (They generally grow vertically during welding before the weld metal has completely solidified.) Piping porosity is frequently referred to as *pin holes* when the porosity extends to the weld surface.

PJP (partial joint penetration). Joint penetration that is intentionally less than complete.

plug weld. A weld made in a circular hole in one member of a joint, fusing that member to another member. A fillet-welded hole shall not be construed as conforming to this definition.

***porosity.** Cavity-type discontinuities formed by gas entrapment during solidification.

***positioned weld.** A weld made in a joint that has been placed to facilitate making the weld.

***postweld heat treatment.** Any heat treatment after welding.

***preheating.** The application of heat to the base metal immediately before welding, brazing, soldering, thermal spraying, or cutting.

preheat temperature (welding). A specified temperature that the base metal shall attain in the welding, brazing, soldering, thermal spraying, or cutting area immediately before these operations are performed.

procedure qualification. The demonstration that welds made by a specific procedure can meet prescribed standards.

procedure qualification record (PQR) (welding). A document providing the actual welding variables used to produce an acceptable test weld and the results of tests conducted on the weld to qualify a WPS. See Form E-1.

PT. Liquid penetrant testing.

Q

qualification. See preferred terms **welder performance qualification** and **procedure qualification**.

R

random sequence. A longitudinal sequence in which the weld bead increments are made at random.

reference level (UT). The decibel reading obtained for a horizontal reference-line height indication from a reference reflector.

reference reflector (UT). The reflector of known geometry contained in the IIW reference block or other approved blocks.

reinforcement of weld. See **weld reinforcement**.

***rejectable discontinuity.** See preferred term **defect**.

resolution (UT). The ability of UT equipment to give separate indications from closely spaced reflectors.

root face. That portion of the groove face within the joint root (see AWS A3.0, Figure B5).

root of joint. See **joint root**.

root of weld. See **weld root**.

root opening. The separation at the joint root between the workpieces.

RT. Radiographic testing.

S

SAW (submerged arc welding). An arc welding process that uses an arc or arcs between a bare metal electrode or electrodes and the weld pool. The arc and molten metal are shielded by a blanket of granular flux on the workpieces. The process is used without pressure and with filler metal from the electrode and sometimes from a supplemental source (welding rod, flux, or metal granules).

*__single electrode.__ One electrode connected exclusively to one power source which may consist of one or more power units.

*__parallel electrode.__ Two electrodes connected electrically in parallel and exclusively to the same power source. Both electrodes are usually fed by means of a single electrode feeder. Welding current, when specified, is the total for the two electrodes.

*__multiple electrodes.__ The combination of two or more single or parallel electrode systems. Each of the component systems has its own independent power source and its own electrode feeder.

scanning level (UT). The dB setting used during scanning, as described in Tables <u>8.4 and 8.5</u>.

*__semiautomatic welding.__ Arc welding with equipment that controls only the filler metal feed. The advance of the welding is manually controlled.

shielding gas. Protective gas used to prevent or reduce atmospheric contamination.

*__single-welded joint (fusion welding).__ In arc and gas welding, any joint welded from one side only.

size of weld. See **weld size**.

slot weld. A weld made in an elongated hole in one member of a joint fusing that member to another member. The hole may be open at one end. A fillet welded slot shall not be construed as conforming to this definition.

SMAW (shielded metal arc welding). An arc welding process with an arc between a covered metal electrode and the weld pool. The process is used with shielding from the decomposition of the electrode covering, without the application of pressure, and with filler metal from the electrode.

sound beam distance (UT). See preferred term **sound path distance**.

sound path distance (UT). The distance between the search unit test material interface and the reflector as measured along the centerline of the sound beam.

spatter. The metal particles expelled during fusion welding that do not form a part of the weld.

<u>**storage phosphor imaging plate (SPIP).** Phosphor imaging plates release stored energy within a phosphor by stimulation with visible light, to produce a luminescent signal.</u>

stringer bead. A type of weld bead made without appreciable weaving motion.

*__stud arc welding (SW).__ An arc welding process that produces coalescence of metals by heating them with an arc between a metal stud, or similar part, and the other workpiece. When the surfaces to be joined are properly heated, they are brought together under pressure. Partial shielding may be obtained by the use of a ceramic ferrule surrounding the stud. Shielding gas or flux may or may not be used.

*__stud base.__ The stud tip at the welding end, including flux and container or metal insert, and 3 mm [1/8 in] of the body of the stud adjacent to the tip.

T

tack weld. A weld made to hold parts of a weldment in proper alignment until the final welds are made.

***tack welder.** A fitter, or someone under the direction of a fitter, who has been qualified to tack weld parts of a weldment to hold them in proper alignment until the final welds are made.

***tandem.** Refers to a geometrical arrangement of electrodes in which a line through the arcs is parallel to the direction of welding.

temporary weld. A weld made to attach a piece or pieces to a weldment for temporary use in handling, shipping, or working on the weldment.

throat of a fillet weld

theoretical throat. The distance from the beginning of the joint root perpendicular to the hypotenuse of the largest right triangle that can be inscribed within the cross section of a fillet weld. This dimension is based on the assumption that the root opening is equal to zero.

actual throat. The shortest distance between the weld root and the face of a fillet weld.

throat of a groove weld. A nonstandard term for **groove weld size**.

T-joint. A joint between two members located approximately at right angles to each other in the form of a T.

toe of weld. See **weld toe**.

***transverse discontinuity.** A weld discontinuity whose major dimension is in a direction perpendicular to the weld axis “X.”

U

undercut. A groove melted into the base metal adjacent to the weld toe or weld root and left unfilled by weld metal.

UT. Ultrasonic testing.

V

***vertical welding position.** The position of welding in which the axis of the weld is approximately vertical [see Figures 7.4, 7.5, 7.6(C), and 7.7(C)].

V-path (UT). The distance a shear wave sound beam travels from the search unit test material interface to the other face of the test material and back to the original surface.

W

weave bead. A type of weld bead made with transverse oscillation.

weld. A localized coalescence of metals or nonmetals produced either by heating the materials to the welding temperature, with or without the application of pressure or by the application of pressure alone, and with or without the use of filler metal.

weldability. The capacity of a material to be welded under the imposed fabrication conditions into a specific, suitably designed structure and to perform satisfactorily in the intended service.

weld axis. A line through the length of a weld, perpendicular to and at the geometric center of its cross section.

weld bead. A weld resulting from a pass. See **stringer bead** and **weave bead**.

welder. One who performs a manual or semiautomatic welding.

***welder certification.** Certification in writing that a welder has produced welds meeting prescribed standards. Certification is only effective when the welder or welding operator meets the currency requirements of Clause 7 Part B.

welder performance qualification. The demonstration of a welder's ability to produce welds meeting specified standards.

weld face. The exposed surface of a weld on the side from which welding was done.

welding. A joining process that produces coalescence of materials by heating them to the welding temperature, with or without the application of pressure alone, and with or without the use of filler metal. See the Master Chart of Welding Processes, AWS A3.0.

welding machine. Equipment used to perform the welding operation. For example, spot welding machine, arc welding machine, and seam welding machine.

welding operator. One who operates adaptive control, automatic, mechanized, or robotic welding equipment.

***welding procedure.** The detailed methods and practices including all joint welding procedures involved in the production of a weldment. See **joint welding procedure**.

welding procedure specification (WPS). A document providing the required variables for a specific application to assure repeatability by properly trained welders and welding operators.

welding sequence. The order of making the welds in a weldment.

weldment. An assembly whose component parts are joined by welding.

weld pass. A single progression of welding along a joint. The result of a pass is a weld bead or layer.

weld reinforcement. Weld metal in excess of the quantity required to fill a joint.

weld root. The points, shown in cross section, at which the root surface intersects the base metal surfaces.

weld size

fillet weld size. For equal leg fillet welds, the leg lengths of the largest isosceles right triangle which can be inscribed within the fillet weld cross section. For unequal leg fillet welds, the leg lengths of the largest right triangle that can be inscribed within the fillet weld cross section.

groove weld size. The joint penetration of a groove weld.

weld tab. Additional material that extends beyond either end of the joint, on which the weld is started or terminated.

weld toe. The junction of the weld face and the base metal.

4. Design of Welded Connections

Part A
General Requirements

4.1 Drawings

4.1.1 Full and complete information regarding location, type, size, and extent of all welds shall be clearly shown on the drawings. The drawings shall clearly distinguish between shop and field welds. Unless specifically indicated in the design, all groove welds, both shop and field, shall be complete joint penetration (CJP) groove welds.

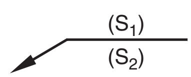
4.1.2 Those joints or groups of joints for which it is especially important that the welding sequence and technique be carefully controlled to minimize shrinkage stresses and distortion shall be so noted on shop and working drawings.

4.1.3 Contract design drawings shall specify the effective weld length and, for partial joint penetration (PJP) groove welds, the required weld size, as defined in 4.3. Shop or working drawings shall specify the groove angles (α and β) and depths (D) applicable for the weld size (S) required for the welding processes and position of welding to be used.

4.1.3.1 It is recommended that contract design drawings show CJP or PJP groove weld requirements. The welding symbol without dimensions designates a CJP weld, as follows:

Complete joint penetration
groove weld (CJP)

The welding symbol with the effective groove weld size (S) above or below the reference line designates a PJP weld as follows:



Where

(S_1) = effective groove weld size, other side
(S_2) = effective groove weld size, arrow side

4.1.3.2 Special groove details shall be specified where required.

4.1.4 Detail drawings shall clearly indicate by welding symbols or sketches the details of groove welded joints and the preparation of material required to make them. Both width and thickness of steel backing shall be detailed.

4.1.5 Any special inspection requirements shall be noted on the drawings or in the specifications.

4.1.6 **Use of Undermatched Filler Metals.** Undermatching filler metal may be used:

(1) For all fillet and PJP groove welds, when consistent with design requirements.

(2) For all CJP groove welds where the stress in the weld is tension or compression parallel to the weld axis, providing shear on the effective weld area meets AASHTO design requirements for all applications.

For CJP groove welds in compression, undermatching up to 70 MPa [10 ksi] may be used. Weld sizes shall be based on the strength of filler metal that is required to be used, or the strength of filler metal that may be used. Weld sizes and weld metal strength levels shall be in conformance with AASHTO Design Specifications. Design drawings shall show the weld size and, where required or allowed, the undermatching filler metal strength classification shall be shown. Shop drawings shall show the weld size and filler metal strength classification when undermatching filler metal is to be used.

4.2 Basic Unit Stresses

Basic unit stresses for base metals and for effective areas of weld metal for application to AASHTO highway bridges shall be as shown in the AASHTO *Standard Specifications for Highway Bridges* or the AASHTO *LRFD Bridge Design Specification*.

4.3 Effective Weld Areas, Lengths, Throats, and Sizes

4.3.1 Groove Welds. The effective area shall be the effective weld length multiplied by the effective groove weld size.

4.3.1.1 The effective weld length for any groove weld, square or skewed, shall be the width of the part joined, perpendicular to the direction of stress.

4.3.1.2 The effective weld size of a CJP groove weld shall be the thickness of the thinner part joined. No increase is allowed for weld reinforcement.

4.3.1.3 The effective weld size of a PJP groove weld shall be the depth of bevel less 3 mm [1/8 in] for grooves having a groove angle less than 60° but not less than 45° at the root of the groove, when made by SMAW or SAW, when made in the vertical or overhead welding positions by GMAW or FCAW.

The effective weld size of a PJP groove weld shall be the depth of bevel, without reduction, for grooves

(1) having a groove angle of 60° or greater at the root of the groove when made by any of the following welding processes: SMAW, SAW, GMAW, FCAW, EGW, or ESW, or

(2) having a groove angle not less than 45° at the root of the groove when made in flat or horizontal positions by GMAW or FCAW.

4.3.1.4 Flare groove joints shall not be used to join structural steel in bridges.

4.3.1.5 The minimum effective weld size of a PJP groove weld shall be as described in Table 4.2.

4.3.2 Fillet Welds. The effective area shall be the effective weld length multiplied by the effective throat. Stress in a fillet weld shall be considered as applied to this effective area, for any direction of applied load.

4.3.2.1 The effective length of a fillet weld shall be the overall length of the full-size fillet, including boxing. No reduction in effective length shall be made for either the start or crater of the weld if the weld is full size throughout its length.

4.3.2.2 The effective length of a curved fillet weld shall be measured along the centerline of the effective throat. If the weld area of a fillet weld in a hole or slot computed from this length is greater than the area found from 4.3.3, then this latter area shall be used as the effective area of the fillet weld.

4.3.2.3 The minimum length of a fillet weld shall be at least four times the nominal size, or the effective size of the weld shall be considered not to exceed 25% of its effective length. Whenever practicable, the minimum length for fillet welds shall be 40 mm [1-1/2 in].

4.3.2.4 The effective throat shall be the shortest distance from the joint root to the weld face of the diagrammatic weld (see Annex A). *NOTE: See Annex B for method of calculating effective throats for fillet welds in skewed T-joints. A convenient tabulation of relative leg sizes (W) for joints with zero root opening (R = 0) that will have the same strength as a 90° fillet weld has been provided for dihedral angles between 60° and 135° in Annex B, Table B.1.*

4.3.3 Plug and Slot Welds. The effective area of a plug or slot weld shall be the nominal area of the hole or slot in the plane of the faying surface.

4.3.4 The effective weld size of a combination PJP groove weld and a fillet weld shall be the shortest distance from the joint root to the weld face of the diagrammatic weld minus 3 mm [1/8 in], for any groove detail requiring such deduction (see Annex A).

Part B
Structural Details

4.4 General

Welded connections shall be designed and detailed to satisfy the strength, stiffness, flexibility, and fatigue requirements of the AASHTO and/or other applicable design specifications.

4.5 Welded Filler Plates

4.5.1 Welded filler plates (see Figures 4.1 and 4.2) are designated Category E fatigue details and shall be avoided when joining tension and reversal of stress members. When the design allows the use of filler plates, they may be used in the following:

(1) Splicing parts of different thicknesses

(2) Connections that, due to existing geometric alignment, shall accommodate offsets to allow simple framing

4.5.2 A filler plate less than 6 mm [1/4 in] thick shall not be used to transfer stress but shall be kept flush with the welded edges of the stress-carrying part. The sizes of welds along such edges shall be increased over the required sizes by an amount equal to the thickness of the filler plate (see Figure 4.1).

4.5.3 Any filler plate 6 mm [1/4 in] or more in thickness shall extend beyond the edges of the splice plate or connection material. It shall be welded to the part on which it is fitted, and the joint shall be of sufficient strength to transmit the splice plate or connection material stress applied at the surface of the filler plate as an eccentric load. The welds joining the splice plate or connection material to the filler plate shall be sufficient to transmit the splice plate or connection material stress and shall be long enough to avoid overstressing the filler plate along the toe of the weld (see Figure 4.2).

4.6 PJP Groove Welds

Joints containing PJP groove welds, made from one side only, shall be restrained to prevent rotation.

Part C
Details of Welded Joints

4.7 Joint Qualification

Details of welded joints that may be used in a prequalified WPS are described in 4.8 through 4.13.

4.7.1 Joint details may depart from the details described in 4.12 and 4.13 only if the Contractor submits the proposed WPSs to the Engineer for approval, and at the Contractor's expense, demonstrates their adequacy in conformance with the requirements of 7.7.5 and 7.12.4 of this code and their conformance with the applicable provisions of Clauses 5, 6, and 7.

4.8 Details of Fillet Welds

4.8.1 The minimum fillet weld size, except for fillet welds used to reinforce groove welds, shall be as shown in Table 4.1, or as calculated using procedures established to prevent cracking in conformance with 6.2.1.2. In both cases, the minimum size shall apply if it is sufficient to satisfy design requirements.

4.8.2 The maximum fillet weld size detailed along edges of material shall be the following:

4.8.2.1 The thickness of the base metal, for metal less than 6 mm [1/4 in] thick (see Figure 4.3, Detail A).

4.8.2.2 2 mm [1/16 in] less than the thickness of base metal, for metal 6 mm [1/4 in] or more in thickness (see Figure 4.3, Detail B), unless the weld is designated on the drawing to be built out to obtain full throat thickness. In the as-welded condition, the distance between the edge of the base metal and the toe of the weld may be more or less than 2 mm [1/16 in], provided the weld size shall be clearly verifiable.

4.8.3 Fillet welds in holes or slots in lap joints may be used to transfer shear or to prevent buckling or separation of lapped parts. These fillet welds may overlap, subject to the provisions of 4.3.2.2. Fillet welds in holes or slots are not to be considered as plug or slot welds.

4.8.4 Fillet welds may be used in skewed T-joints having a dihedral angle (ψ) of not less than 60° nor more than 135° (see Figure 4.3, Details C and D). Detail D shall be used when R_n would exceed 5 mm [3/16 in] using Detail C.

4.8.5 When the design allows intermittent fillet welds, the minimum length of an intermittent fillet weld shall be as described in 4.3.2.3.

4.8.6 Minimum spacing and dimensions of holes or slots when fillet welding is used shall conform to the requirements of 4.9.

4.8.7 Fillet welds supporting a tensile force that is not parallel to the axis of the weld shall not terminate at the corners of parts or members, but shall be returned continuously, full size, around the corner for a length equal to twice the weld size where such return can be made in the same plane. Boxing shall be indicated on design and detail drawings.

4.8.8 Fillet welds deposited on the opposite sides of a common plane of contact between two parts shall be interrupted at a corner common to both welds (see Figure 4.6).

4.9 Details of Plug and Slot Welds

4.9.1 The details of plug and slot welds made by the SMAW, GMAW, or FCAW processes are described in 4.9.2 through 4.9.7 and 5.3.1.1.

4.9.1.1 Plug and slot welds may be used without performing the WPS qualification described in 7.7.5, provided the technique provisions of 6.23, 6.24, and 6.25, as applicable, are met.

4.9.2 The minimum diameter of the hole for a plug weld shall be no less than the thickness of the part containing it plus 8 mm [5/16 in]. The maximum diameter shall equal the minimum diameter plus 3 mm [1/8 in] or 2-1/4 times the thickness of the member, whichever is greater.

4.9.3 The minimum center-to-center spacing of plug welds shall be four times the diameter of the hole.

4.9.4 The length of the slot for a slot weld shall not exceed ten times the thickness of the part containing it. The width of the slot shall be no less than the thickness of the part containing it plus 8 mm [5/16 in]. The maximum width shall equal the minimum width plus 3 mm [1/8 in] or 2-1/4 times the thickness of the member, whichever is greater.

4.9.5 The ends of the slot shall be semicircular or shall have the corners rounded to a radius not less than the thickness of the part containing it, except those ends that extend to the edge of the part.

4.9.6 The minimum spacing of lines of slot welds in a direction transverse to their length shall be four times the width of the slot. The minimum center-to-center spacing in a longitudinal direction on any line shall be two times the length of the slot.

4.9.7 The depth of filling of plug or slot welds in metal 16 mm [5/8 in] thick or less shall be equal to the thickness of the material. In metal over 16 mm [5/8 in] thick, it shall be at least one-half the thickness of the material, but no less than 16 mm [5/8 in].

4.10 Lap Joints

4.10.1 The minimum overlap of parts in stress-carrying lap joints shall be five times the thickness of the thinner part. Unless lateral deflection of the parts is prevented, they shall be connected by at least two transverse lines of fillet, plug, or slot welds or by two or more longitudinal fillet or slot welds.

4.10.2 If longitudinal fillet welds are used alone in lap joints of end connections, the length of each fillet weld shall be no less than the perpendicular distance between the welds (shown as dotted line in Figure 4.6). The transverse spacing of the welds shall not exceed 16 times the thickness of the connected thinner part unless suitable provision is made (as by intermediate plug or slot welds) to prevent buckling or separation of the parts. The longitudinal fillet weld may be either at the edges of the member or in slots.

4.10.3 When fillet welds in holes or slots are used, the clear distance from the edge of the hole or slot to the adjacent edge of the part containing it, measured perpendicular to the direction of stress, shall be no less than five times the thickness of the part nor less than two times the width of the hole or slot. The strength of the part shall be determined from the critical net section of the base metal.

4.10.4 Lap joints are Category E details and should be avoided, when possible, in members subject to tension or reversal of stresses.

4.11 Corner and T-Joints

4.11.1 Corner and T-joints subject to bending perpendicular to the joint shall have their welds arranged to avoid concentration of tensile stress at the root of any weld.

4.11.2 Corner and T-joints parallel to the direction of computed stress between components of built-up members designed for axial stress need not be CJP groove welds. Fillet welds or a combination of PJP welds and reinforcing fillet welds may be used.

4.11.3 Groove welds in corner and T-joints shall be reinforced with fillet welds with a leg size equal to or greater than T/4, but which need not exceed 10 mm [3/8 in]. T shall be defined as the thickness of the thinner part being joined.

4.12 CJP Groove Welds

4.12.1 **Dimensional Tolerances.** Dimensions of groove welds specified on design or detailed drawings may vary as shown in Figure 4.4.

4.12.2 **Corner Joints.** For corner joints using beveled single-bevel groove welds, either plate may be beveled, provided the basic groove configuration is not changed and adequate edge distance is maintained to support the welding operations without excessive melting. Joint preparation that bevels the plate that will be stressed in the short transverse direction will help to reduce lamellar tearing.

4.13 PJP Groove Welds (see Figure 4.5)

4.13.1 **Definition.** Except as provided in Figure 4.4, groove welds without steel backing, welded from one side, and groove welds welded from both sides but without backgouging, are considered PJP groove welds unless qualified as CJPs by 7.7.5.

4.13.1.1 All PJP groove welds made by GMAW-S shall be qualified by the WPS qualification tests described in 7.12.4.

4.13.2 **Minimum Effective Weld Size.** The minimum effective weld size of PJP square-, single- or double-V-, bevel-, J-, and U-groove welds shall be as shown in Table 4.2.

Shop or working drawings shall specify the groove depths (D) applicable for the effective weld size (S) required for the welding process and position of welding to be used.

4.13.3 **Corner Joints.** For corner joints using single-bevel groove welds, either plate may be beveled, provided the basic groove configuration is not changed and adequate edge distance is maintained to support the welding operations without excessive melting. Joint preparation that bevels the plate that will be stressed in the short-transverse direction will help to reduce lamellar tearing.

4.14 Prohibited Types of Joints and Welds

The joints and welds described in the following paragraphs shall be prohibited:

(1) All PJP groove welds in butt joints except those conforming to 4.17.3

(2) CJP groove welds, in all members carrying calculated stress or in secondary members subject to tension or the reversal of stress, made from one side only without any backing, or with backing other than steel, that has not been qualified in conformance with 7.7.5 and 7.12.4

(3) Intermittent groove welds

(4) Intermittent fillet welds, except as approved by the Engineer

(5) Flat position bevel-groove and J-groove welds in butt joints where V-groove and U-groove welds are practicable

(6) Plug and slot welds in members subject to tension and reversal of stress

4.15 Combinations of Welds

If two or more of the general types of welds (groove, fillet, plug, slot) are combined in a single joint, their allowable capacity shall be computed with reference to the axis of the group in order to determine the allowable capacity of the combination (see Annex A). However, such methods of adding individual capacities of welds do not apply to fillet welds reinforcing CJP groove welds.

4.16 Welds in Combination with Rivets and Bolts

In new work, rivets or bolts in combination with welds shall not be considered as sharing the stress, and the welds shall be provided to carry the entire stress for which the connection is designed. Bolts or rivets used in assembly may be left in place if their removal is not specified. If bolts are to be removed, the plans should indicate whether holes should be filled and in what manner.

4.17 Connection Details

4.17.1 Eccentricity of Connections

4.17.1.1 Eccentricity between intersecting parts and members shall be avoided insofar as practical.

4.17.1.2 In designing welded joints, adequate provision shall be made for bending stresses due to eccentricity, if any, in the disposition and section of base metal parts and in the location and types of welded joints.

4.17.1.3 For members having symmetrical cross sections, the connection welds shall be arranged symmetrically about the axis of the member, or proper allowance shall be made for unsymmetrical distribution of stresses.

4.17.1.4 For axially stressed angle members, the center of gravity of the connecting welds shall preferably lie between the line of the center of gravity of the angle's cross section and the centerline of the connected leg. If the center of gravity of the connecting weld lies outside of this zone, the total stresses, including those due to the eccentricity from the center of gravity of the angle, shall not exceed those allowed by this code.

4.17.2 Connections or Splices—Tension and Compression Members. Connections or splices of tension or compression members made by groove welds shall have CJP groove welds. Connections or splices made with fillet welds, except as noted in 4.17.3, shall be designed for an average of the calculated stress and the strength of the member, but not less than 75% of the strength of the member, or if there is repeated application of load, the maximum stress or stress range in such connection or splice shall not exceed the fatigue stress allowed by the applicable AASHTO specification.

4.17.3 Connections or Splices in Compression Members with Finished-to-Bear Joints. If members subject only to compression are spliced and a finished-to-bear fit is provided, the welding shall be arranged to hold all parts in alignment, and welds and contact areas shall be proportioned to each carry 50% of the computed stress in the member. Where such members are finished to achieve direct bearing on base plates, contact tolerances shall satisfy the second paragraph of 5.5.9 and there shall be sufficient welding to hold all parts securely in place.

4.17.4 Connections of Components of Built-Up Members. When a member is built up of two or more pieces, the pieces shall be connected along their longitudinal joints by sufficient continuous welds to make the pieces act in unison.

4.17.5 Transition of Thicknesses or Widths at Butt Joints

4.17.5.1 Butt joints between parts having unequal thicknesses and subject to tensile stress shall have a smooth transition between the offset surfaces at a slope of no more than 1 transverse to 2.5 longitudinal with the surface of either part. The transition may be accomplished by sloping weld surfaces, by chamfering the thicker part, or by a combination of the two methods (see Figure 4.7).

4.17.5.2 In butt joints between parts of unequal thickness that are subject only to shear or compressive stress, transition of thickness shall be accomplished as described in 4.17.5.1 when offset between surfaces at either side of the joint is greater than the thickness of the thinner part connected. When the offset is equal to or less than the thickness of the thinner part connected, the face of the weld shall be sloped no more than 1 transverse to 2.5 longitudinal from the surface of the thinner part, or shall be sloped to the surface of the thicker part if this requires a lesser slope with the following exception:

Truss member joints and beam and girder flange joints shall be made with smooth transitions of the type described in 4.17.5.1.

4.17.5.3 Butt joints between parts having unequal width and subject to tensile stress shall have a smooth transition between offset edges at a slope transition of no more than 1 transverse to 2.5 longitudinal with the edge of either part or shall be transitioned with a 600 mm [24 in] minimum radius tangent to the narrower part at the center of the butt joint (see Figure 4.8). The stress range for the transitional detail shall be as allowed by AASHTO design specifications.

4.17.6 Girders and Beams

4.17.6.1 Connections or splices in beams or girders when made by groove welds shall have CJP groove welds. Connections or splices made with fillet or plug welds shall be designed for the average of the calculated stress and the strength of the member, but no less than 75 percent of the strength of member. When there is repeated application of load, the maximum stress or stress range in such connections or splices shall not exceed the fatigue stress allowed by the AASHTO specification.

4.17.6.2 Splices between sections of rolled beams or built-up girders shall preferably be made in a single transverse plane. Shop splices of webs and flanges in built-up girders, made before the webs and flanges are joined to each other, may be located in a single transverse plane or multiple transverse planes, but the fatigue stress provisions of the AASHTO specifications shall apply.

4.17.6.3 Noncontinuous Beams. The connections at the ends of noncontinuous beams shall be designed with flexibility so as to avoid excessive secondary stresses due to bending. Seated connections with a flexible or guiding device to prevent end twisting are recommended.

Table 4.1
Minimum Fillet Weld Size[a, b] (see 4.8.1)

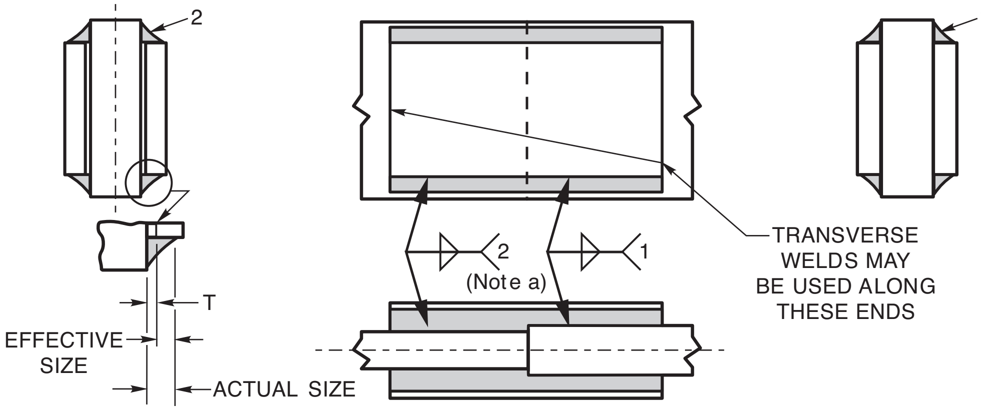
Base Metal Thickness of Thicker Part Joined (T)	Minimum Size of Fillet Weld	
T ≤ 20 mm [3/4 in]	6 mm [1/4 in]	Single-pass welds shall be used
T > 20 mm [3/4 in]	8 mm [5/16 in]	

[a] Smaller fillet welds may be approved by the Engineer based on applied stress and the use of appropriate preheat.
[b] Except that the weld size need not exceed the thickness of the thinner part joined. For this exception, particular care should be taken to provide sufficient preheat to ensure weld soundness.

Table 4.2
Minimum Effective Weld Size for PJP Groove Welds[a, b] (see 4.13.2)

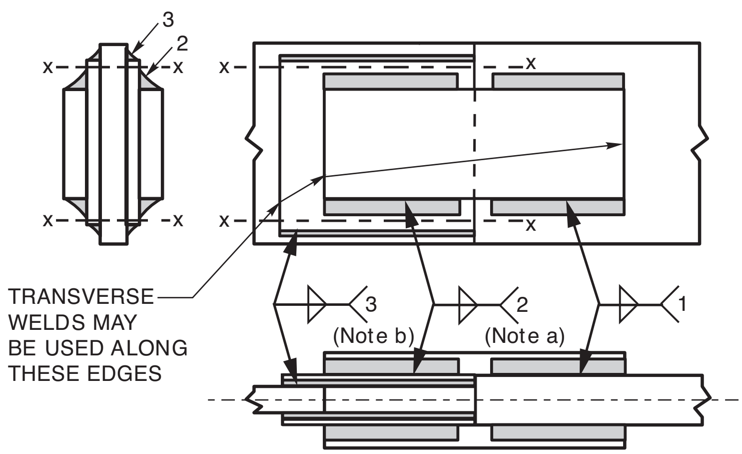
Base Metal Thickness of Thicker Part Joined (T)	Minimum Effective Weld Size
T ≤ 20 mm [3/4 in]	6 mm [1/4 in]
T > 20 mm [3/4 in]	8 mm [5/16 in]

[a] Smaller welds may be approved by the Engineer based on applied stress and the use of appropriate preheat.
[b] Except that the weld size need not exceed the thickness of the thinner part.



[a] The effective area of weld 2 shall equal that of weld 1, but its size shall be its effective size plus the thickness of the filler T.

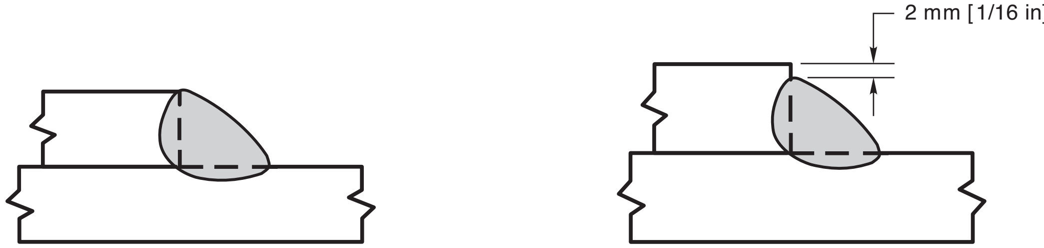
Figure 4.1—Filler Plates Less Than 6 mm [1/4 in] Thick (see 4.5.1)



[a] The effective area of weld shall equal that of weld 1. The length of weld 2 shall be sufficient to avoid overstressing the filler plate in shear along planes x-x.

[b] The effective area of weld 3 shall at least equal that of weld 1 and there shall be no overstress of the ends of weld 3 resulting from the eccentricity of the forces acting on the filler plate.

Figure 4.2—Filler Plates 6 mm [1/4 in] or Thicker (see 4.5.3)



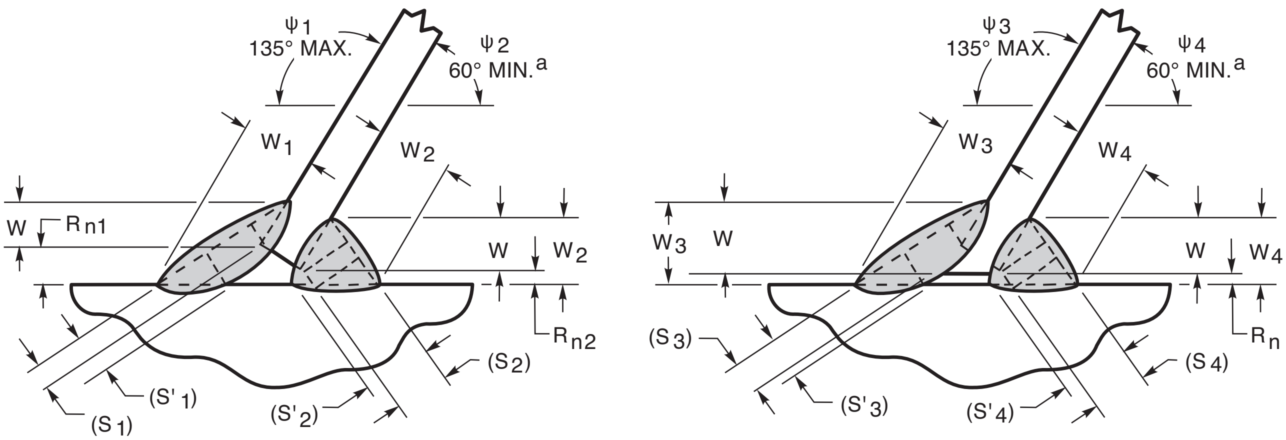
BASE METAL LESS THAN 6 mm [1/4 in] THICK

(A)

BASE METAL 6 mm [1/4 in] OR MORE IN THICKNESS

(B)

MAXIMUM DETAILED SIZE OF FILLET WELD ALONG EDGES



(C)

(D)

SKEWED T-JOINTS

[a] Angles smaller than 60° are allowed; however, in such cases, the weld is considered to be a PJP groove weld.

Note: (S)(n), (S´)(n) = effective throats dependent on magnitude of root opening (R_n) (see 5.3.1). Subscript (n) represents 1, 2, 3, or 4.

Figure 4.3—Details for Fillet Welds (see 4.8)

Legend for Figures 4.4 and 4.5

Symbols for joint types
B — butt joint
C — corner joint
T — T-joint
BC — butt or corner joint
TC — T- or corner joint
BTC — butt, T-, or corner joint

Welding processes
SMAW — shielded metal arc welding
GMAW — gas metal arc welding
FCAW — flux cored metal arc welding
SAW — submerged arc welding

Symbols for base-metal thickness and penetration
L — limited thickness–CJP
U — unlimited thickness–CJP
P — PJP

Welding positions
F — flat
H — horizontal
V — vertical
OH — overhead

Symbol for weld types
1 — square-groove
2 — single-V-groove
3 — double-V-groove
4 — single-bevel-groove
5 — double-bevel-groove
6 — single-U-groove
7 — double-U-groove
8 — single-J-groove
9 — double-J-groove

Dimensions
R — Root Opening
α, β — Groove Angles
f — Root Face
r — J- or U-groove Radius
D, D_1, D_2 — PJP Groove Weld Depth of Groove
S, S_1, S_2 — PJP Groove Weld Sizes corresponding to S, S_1, S_2, respectively

Symbols for welding processes if not SMAW
S — SAW
G — GMAW
F — FCAW

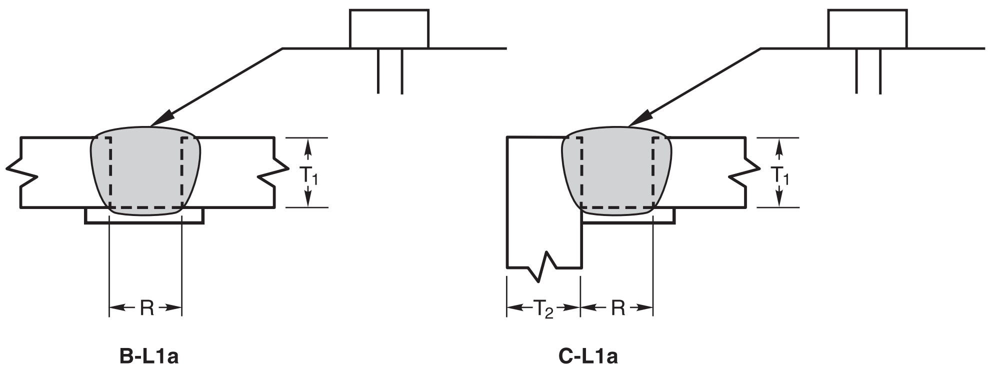
Joint Designation
The lower case letters, e.g., a, b, c, etc., are used to differentiate between joints that would otherwise have the same joint designation.

Notes for Figures 4.4 and 4.5

[a] Groove preparations detailed for SMAW joints may be used for GMAW or FCAW.
[b] Joint shall be welded from one side only.
[c] Backgouge root to sound metal before welding second side.
[d] Minimum weld size (S) as shown in Table 4.2; S as specified on drawings.
[e] Evidence of CJP shall be required (see 6.7.4).
[f] Double-groove welds may have grooves of unequal depth, but the depth of the shallower groove shall be no less than one-fourth of the thickness of the thinner part joined.
[g] Double-groove welds may have grooves of unequal depth, provided they conform to the limitations of Note d. Also the weld size (S), less any reduction, applies individually to each groove.
[h] The orientation of the two members in the joints may vary from 135° to 180° provided that the basic joint configuration (groove angle, root face, root opening) remains the same and that the design weld size is maintained.
[i] For corner and T-joints, the member orientation may be changed provided the groove angle is maintained as specified.
[j] The member orientation may be changed provided that the groove dimensions is maintained as specified.
[k] The orientation of the two members in the joints may vary from 45° to 135° for corner joints and from 45° to 90° for T-joints, provided that the basic joint configuration (groove angle, root face, root opening) remains the same and that the design weld size is maintained.
[l] These joint details shall not be used where V-groove or U-groove details are practicable (see 4.14).

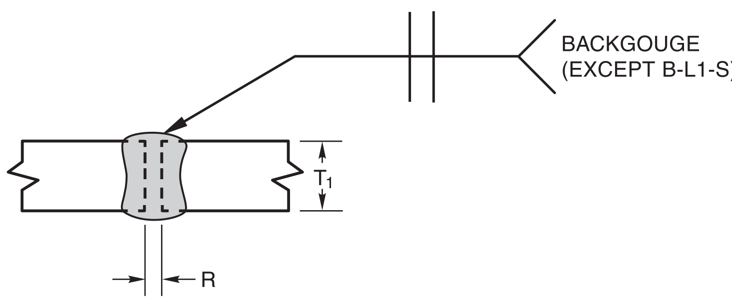
See Notes on Page 27

Square-groove weld (1)
Butt joint (B)
Corner joint (C)



Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Gas Shielding for FCAW	Notes
					Tolerances				
		T_1	T_2	Root Opening	As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)			
SMAW	B-L1a	6 max.	—	$R = T_1$	+2, –0	+6, –2	All	—	a, h
	C-L1a	6 max.	U	$R = T_{1s}$	+2, –0	+6, –2	All	—	a
FCAW GMAW	B-L1a-GF	10 max.	—	$R = T_1$	+2, –0	+6, –2	All	Not required	h

Square-groove weld (1)
Butt joint (B)

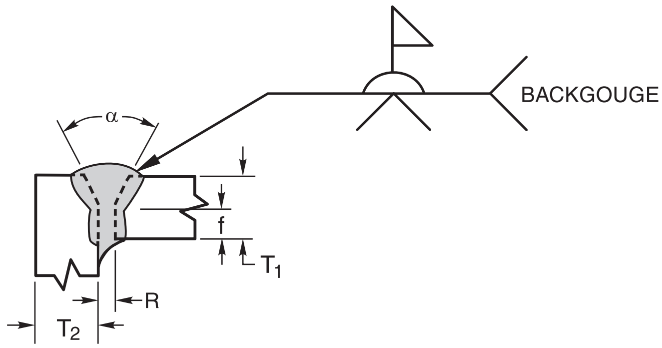


Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Gas Shielding for FCAW	Notes
					Tolerances				
		T_1	T_2	Root Opening	As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)			
SMAW	B-L1b	6 max.	—	$R = \frac{T_1}{2}$	+2, –0	+2, –3	All	—	a, c, h
GMAW FCAW	B-L1b-GF	10 max.	—	R = 0 to 3	+2, –0	+2, –3	All	Not required	c, h
SAW	B-L1-S	10 max.	—	R = 0	±0	+2, –0	F	—	e, h
SAW	B-L1a-S	16 max.	—	R = 0	±0	+2, –0	F	—	c, h

Figure 4.4—Details of Welded Joints for CJP Groove Welds (see 4.12.1)
(Dimensions in Millimeters)

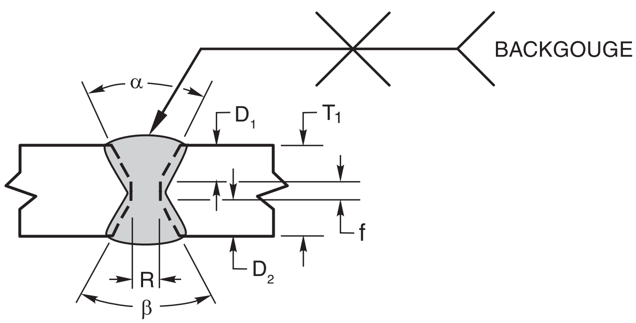
See Notes on Page 27

Single-V-groove weld (2)
Corner joint (C)



Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening Root Face Groove Angle	Tolerances: As Detailed (see 4.12.1)	Tolerances: As Fit-Up (see 5.3.4)			
SMAW	C-U2	U	U	R = 0 to 3 f = 0 to 3 α = 60°	+2, –0 +2, –0 +10°, –0°	+2, –3 Not limited +10°, –5°	All	—	a, c, k
GMAW FCAW	C-U2-GF	U	U	R = 0 to 3 f = 0 to 3 α = 60°	+2, –0 +2, –0 +10°, –0°	+2, –3 Not limited +10°, –5°	All	Not required	c, k
SAW	C-U2b-S	25 min.	U	R = 0 f = 6 max. α = 60°	±0 +6, –0 +10°, –0°	+2, –0 ±2 +10°, –5°	F	—	c, k

Double-V-groove weld (3)
Butt joint (B)



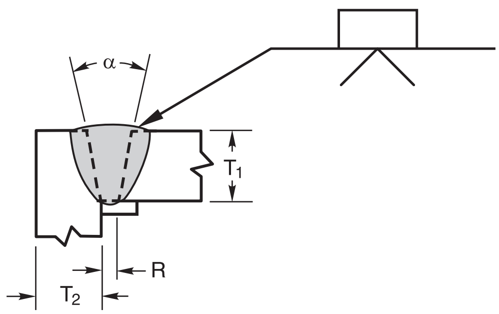
For B-U3c-S only		
T_1 Over	T_1 to	D_1
50	60	35
60	80	45
80	90	55
90	100	60
100	120	70
120	140	80
140	160	95
For T_1 > 160 or $T_1 \leq 50$ $D_1 = 2/3 (T_1 – 6)$		

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening Root Face Groove Angle	Tolerances: As Detailed (see 4.12.1)	Tolerances: As Fit-Up (see 5.3.4)			
SMAW	B-U3b	U	—	R = 0 to 3 f = 0 to 3 α = β = 60°	+2, –0 +2, –0 +10°, –0°	+2, –3 Not limited +10°, –5°	All	—	a, c, f, h
GMAW FCAW	B-U3-GF						All	Not required	c, f, h
SAW	B-U3c-S	U	—	R = 0 f = 6 min. α = β = 60° To find D_1 see table above: $D_2 = T_1 – (D_1 + f)$	+2, –0 +6, –0 +10°, –0°	+2, –0 +6, –0 +10°, –5°	F	—	c, f, h

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

See Notes on Page 27

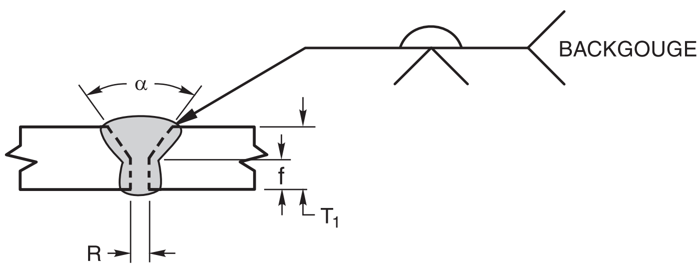
Single-V-groove weld (2)
Corner joint (C)



Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
R = +2, –0	+6, –2
α = +10°, –0°	+10°, –5°

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation		Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening	Groove Angle			
SMAW	C-U2a	U	U	R = 6	α = 45°	All	—	a, k
				R = 10	α = 30°	F, V, OH	—	a, k
				R = 12	α = 20°	F, V, OH	—	a, k
GMAW FCAW	C-U2a-GF	U	U	R = 5	α = 30°	F, V, OH	Required	k
				R = 10	α = 30°	F, V, OH	Not req.	k
				R = 6	α = 45°	F, V, OH	Not req.	k
SAW	C-L2a-S	50 max.	U	R = 6	α = 30°	F	—	k
SAW	C-U2-S	U	U	R = 16	α = 20°	F	—	k

Single-V-groove weld (2)
Butt joint (B)

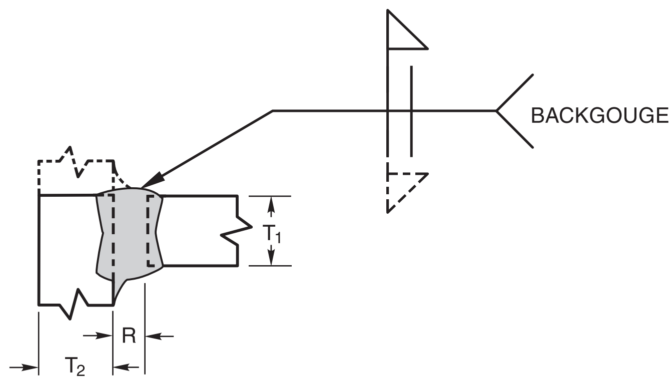


Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Gas Shielding for FCAW	Notes
				Root Opening Root Face Groove Angle	Tolerances				
		T_1	T_2		As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)			
SMAW	B-U2	U	—	R = 0 to 3 f = 0 to 3 α = 60°	+2, –0 +2, –0 +10°, –0°	+2, –3 Not limited +10°, –5°	All	—	a, c, h
GMAW FCAW	B-U2-GF	U	—	R = 0 to 3 f = 0 to 3 α = 60°	+2, –0 +2, –0 +10°, –0°	+2, –3 Not limited +10°, –5°	All	Not required	c, h
SAW	B-L2c-S	Over 12 to 25	—	R = 0 f = 6 min. α = 60°	R = ±0 f = +6, –0 α = +10°, –0°	+2, –0 Not limited +10°, –5°	F	—	c, h
		Over 25 to 38	—	R = 0 f = 10 min. α = 60°					
		Over 38 to 50	—	R = 0 f = 12 min. α = 60°					

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

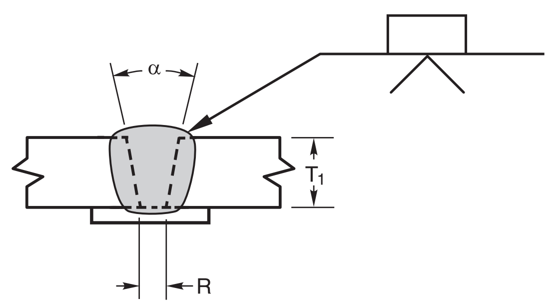
See Notes on Page 27

Square-groove weld (1)
T-joint (T)
Corner joint (C)



Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Gas Shielding for FCAW	Notes
					Tolerances				
		T_1	T_2	Root Opening	As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)			
SMAW	TC-L1b	6 max.	U	$R = \frac{T_1}{2}$	+2, –0	+2, –3	All	—	a, c
GMAW FCAW	TC-L1-GF	10 max.	U	R = 0 to 3	+2, –0	+2, –3	All	Not required	c
SAW	TC-L1-S	10 max.	U	R = 0	±0	+2, –0	F	—	c

Single-V-groove weld (2)
Butt joint (B)



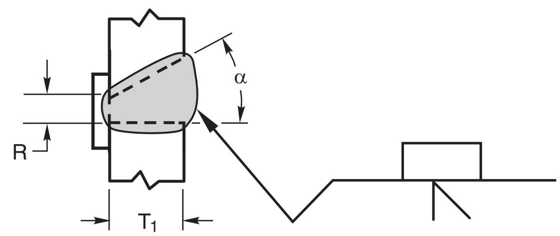
Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
R = +2, –0	+6, –2
α = +10°, –0°	+10°, –5°

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation		Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening	Groove Angle			
SMAW	B-U2a	U	—	R = 6	α = 45°	All	—	a, h
				R = 10	α = 30°	F, V, OH	—	a, h
				R = 12	α = 20°	F, V, OH	—	a, h
GMAW FCAW	B-U2a-GF	U	—	R = 5	α = 30°	F, V, OH	Required	h
				R = 10	α = 30°	F, V, OH	Not req.	h
				R = 6	α = 45°	F, V, OH	Not req.	h
SAW	B-L2a-S	50 max.	—	R = 6	α = 30°	F	—	h
SAW	B-U2-S	U	—	R = 16	α = 20°	F	—	h

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

See Notes on Page 27

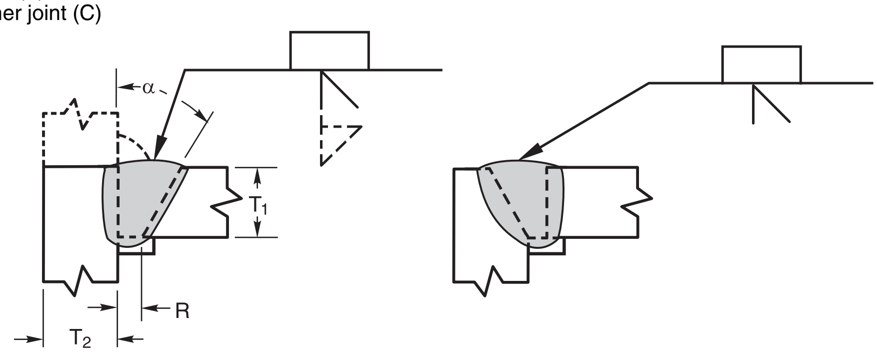
Single-bevel-groove weld (4)
Butt joint (B)



Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
R = +2, –0	+6, –2
α = +10°, –0°	+10°, –5°

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation		Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening	Groove Angle			
SMAW	B-U4a	U	—	R = 6	α = 45°	F, H	—	a, h, l
				R = 10	α = 30°	F, H	—	a, h, l
GMAW FCAW	B-U4a-GF	U	—	R = 5	α = 30°	H	Required	h
				R = 6	α = 45°	H	Not req.	h
				R = 10	α = 30°	H	Not req.	h

Single-bevel-groove weld (4)
T-joint (T)
Corner joint (C)



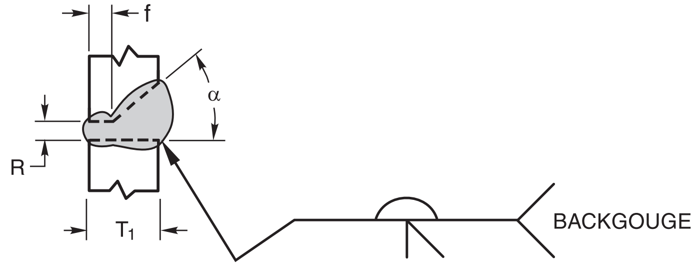
Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
R = +2, –0	+6, –2
α = +10°, –0°	+10°, –5°

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation		Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening	Groove Angle			
SMAW	TC-U4a	U	U	R = 6	α = 45°	All	—	a, k
				R = 10	α = 30°	F, OH, H	—	a, k
GMAW FCAW	TC-U4a-GF	U	U	R = 5	α = 30°	All	Required	k
				R = 10	α = 30°	F	Not req.	k
				R = 6	α = 45°	All	Not req.	k
SAW	TC-U4a-S	U	U	R = 10	α = 30°	F	—	k
				R = 6	α = 45°			

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

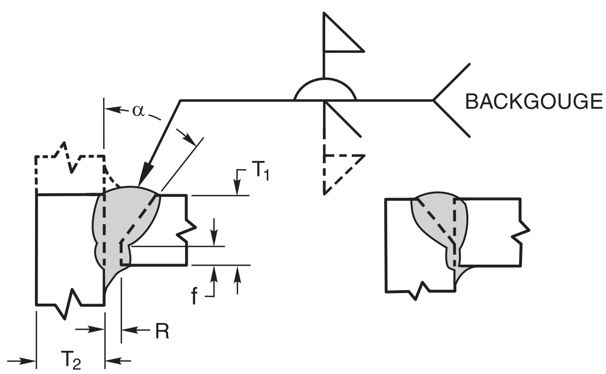
See Notes on Page 27

Single-bevel-groove weld (4)
Butt joint (B)



Welding Process	Joint Designation	Base Metal Thickness (U = unlimited) T_1	T_2	Groove Preparation: Root Opening	Tolerances: As Detailed (see 4.12.1)	Tolerances: As Fit-Up (see 5.3.4)	Allowed Welding Positions	Gas Shielding for FCAW	Notes
SMAW	B-U4b	U	—	R = 0 to 3 f = 0 to 3 α = 45°	+2, −0 +2, −0 +10°, −0°	+2, −3 Not limited 10°, −5°	F, H	—	a, c, h, l
GMAW FCAW	B-U4b-GF	U	—				H	Not required	c, h

Single-bevel-groove weld (4)
T-joint (T)
Corner joint (C)

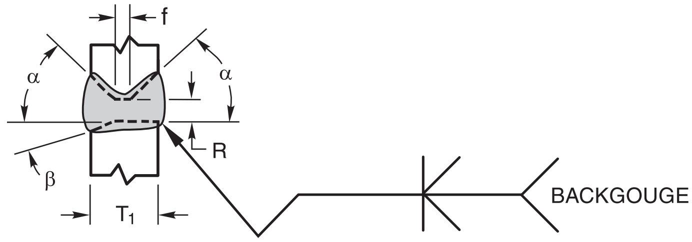


Welding Process	Joint Designation	Base Metal Thickness (U = unlimited) T_1	T_2	Groove Preparation: Root Opening Root Face Groove Angle	Tolerances: As Detailed (see 4.12.1)	Tolerances: As Fit-Up (see 5.3.4)	Allowed Welding Positions	Gas Shielding for FCAW	Notes
SMAW	TC-U4b	U	U	R = 0 to 3 f = 0 to 3 α = 45°	+2, −0 +2, −0 +10°, −0°	+2, −3 Not limited 10°, −5°	All	—	a, c, k
GMAW FCAW	TC-U4b-GF	U	U				All	Not required	c, k
SAW	TC-U4b-S	U	U	R = 0 f = 6 max. α = 60°	±0 +0, −3 +10°, −0°	+6, −0 ±2 10°, −5°	F	—	c, k

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

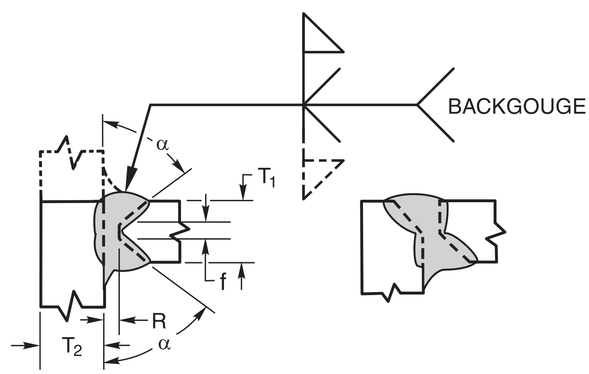
See Notes on Page 27

Double-bevel-groove weld (5)
Butt joint (B)



Welding Process	Joint Designation	Base Metal Thickness (U = unlimited) T_1	T_2	Groove Preparation: Root Opening Root Face Groove Angle	Tolerances: As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)	Allowed Welding Positions	Gas Shielding for FCAW	Notes
SMAW	B-U5a	U	—	R = 0 to 3 f = 0 to 3 α = 45° β = 0° to 15°	+2, –0 +2, –0 α + β +10° –0°	+2, –3 Not limited α + β +10° –5°	F, H	—	a, c, f, h, l
GMAW FCAW	B-U5-GF	U	—	R = 0 to 3 f = 0 to 3 α = 45° β = 0° to 15°	+2, –0 +2, –0 α + β = +10°, –0°	+2, –3 Not limited α + β = +10°, –5°	H	Not required	c, f, h

Double-bevel-groove weld (5)
T-joint (T)
Corner joint (C)

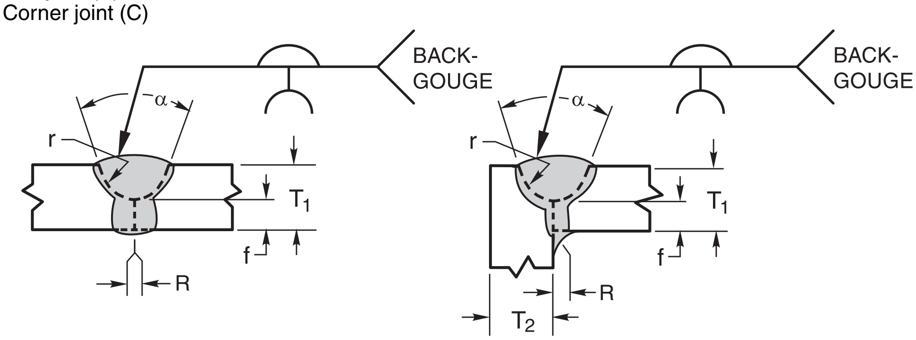


Welding Process	Joint Designation	Base Metal Thickness (U = unlimited) T_1	T_2	Groove Preparation: Root Opening Root Face Groove Angle	Tolerances: As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)	Allowed Welding Positions	Gas Shielding for FCAW	Notes
SMAW	TC-U5b	U	U	R = 0 to 3 f = 0 to 3 α = 45°	+2, –0 +2, –0 +10°, –0°	+2, –3 Not limited +10°, –5°	All	—	a, c, f, k
GMAW FCAW	TC-U5-GF	U	U				All	Not required	c, f, k
SAW	TC-U5-S	U	U	R = 0 f = 5 max. α = 60°	±0 +0, –5 +10°, –0°	+2, –0 ±2 +10°, –5°	F	—	c, f, k

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

See Notes on Page 27

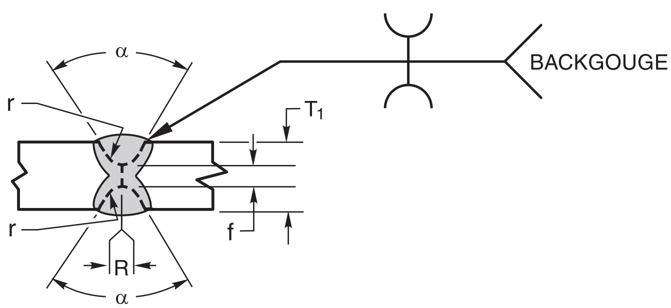
Single-U-groove weld (6)
Butt joint (B)
Corner joint (C)



Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
R = +2, –0	+2, –3
α = +10°, –0°	+10°, –5°
f = ±2	Not Limited
r = +3, –0	+3, –0

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation				Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening	Groove Angle	Root Face	Groove Radius			
SMAW	B-U6	U	U	R = 0 to 3	α = 45°	f = 3	r = 6	All	—	a, c, h
				R = 0 to 3	α = 20°	f = 3	r = 6	F, OH	—	a, c, h
	C-U6	U	U	R = 0 to 3	α = 45°	f = 3	r = 6	All	—	a, c, k
				R = 0 to 3	α = 20°	f = 3	r = 6	F, OH	—	a, c, k
GMAW FCAW	B-U6-GF	U	U	R = 0 to 3	α = 20°	f = 3	r = 6	All	Not req.	c, h
	C-U6-GF	U	U	R = 0 to 3	α = 20°	f = 3	r = 6	All	Not req.	c, k
SAW	B-U6-S	16 min.	16 min.	R = 0	α = 20°	f = 6 min.	r = 6	F	—	c, h
	C-U6-S	16 min.	16 min.	R = 0	α = 20°	f = 6 min.	r = 6	F	—	c, k

Double-U-groove weld (7)
Butt joint (B)



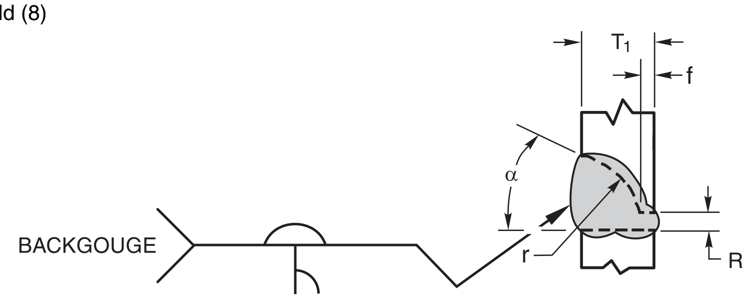
Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
For B-U7 and B-U7-GF	
R = +2, –0	+2, –3
α = +10°, –0°	+10°, –5°
f = ±2, –0	Not Limited
r = +6, –0	±2
For B-U7-S	
R = ±0	+2, –0
f = +0, –6	±2

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation				Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening	Groove Angle	Root Face	Groove Radius			
SMAW	B-U7	U	—	R = 0 to 3	α = 45°	f = 3	r = 6	All	—	a, c, f, h
				R = 0 to 3	α = 20°	f = 3	r = 6	F, OH	—	a, c, f, h
GMAW FCAW	B-U7-GF	U	—	R = 0 to 3	α = 20°	f = 3	r = 6	All	Not required	c, f, h
SAW	B-U7-S	U	—	R = 0	α = 20°	f = 6 max.	r = 6	F	—	c, f, h

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

See Notes on Page 27

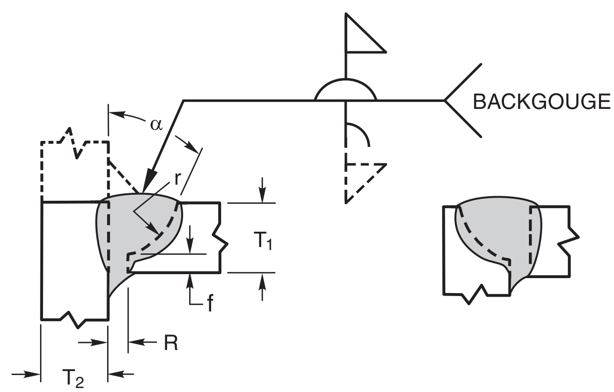
Single-J-groove weld (8)
Butt joint (B)



Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
R = +2, –0	+2, –3
α = +10°, –0°	+10°, –5°
f = +2, –0	Not Limited
r = +6, –0	±2

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation				Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening	Groove Angle	Root Face	Groove Radius			
SMAW	B-U8	U	—	R = 0 to 3	α = 45°	f = 3	r = 10	F, H	—	a, c, h, l
GMAW FCAW	B-U8-GF	U	—	R = 0 to 3	α = 30°	f = 3	r = 10	H	Not required	c, h

Single-J-groove weld (8)
T-joint (T)
Corner joint (C)



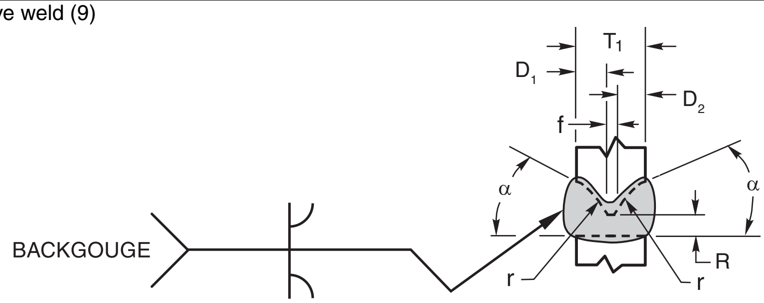
Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
R = +2, –0	+2, –3
α = +10°, –0°	+10°, –5°
f = +2, –0	Not Limited
r = +6, –0	±2

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation				Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening	Groove Angle	Root Face	Groove Radius			
SMAW	TC-U8a	U	U	R = 0 to 3	α = 45°	f = 3	r = 10	All	—	a, c, h
				R = 0 to 3	α = 30°	f = 3	r = 10	F, OH	—	a, c, h
GMAW FCAW	TC-U8a-GF	U	U	R = 0 to 3	α = 30°	f = 3	r = 10	All	Not required	c, h
SAW	TC-U8a-S	16 min.	16 min.	R = 0	α = 30°	f = 6 min.	r = 10	F	—	c, h

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

See Notes on Page 27

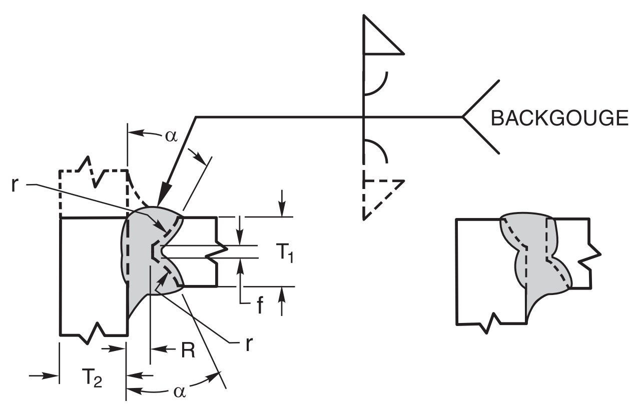
Double-J-groove weld (9)
Butt joint (B)



Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
R = +2, –0	+2, –3
α = +10°, –0°	+10°, –5°
f = +2, –0	Not Limited
r = +3, –0	±2

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation				Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening	Groove Angle	Root Face	Groove Radius			
SMAW	B-U9	U	—	R = 0 to 3	α = 45°	f = 3	r = 10	F, H	—	a, c, f, h, l
GMAW FCAW	B-U9-GF	U	—	R = 0 to 3	α = 30°	f = 3	r = 10	H	Not required	c, f, h

Double-J-groove weld (9)
T-joint (T)
Corner joint (C)



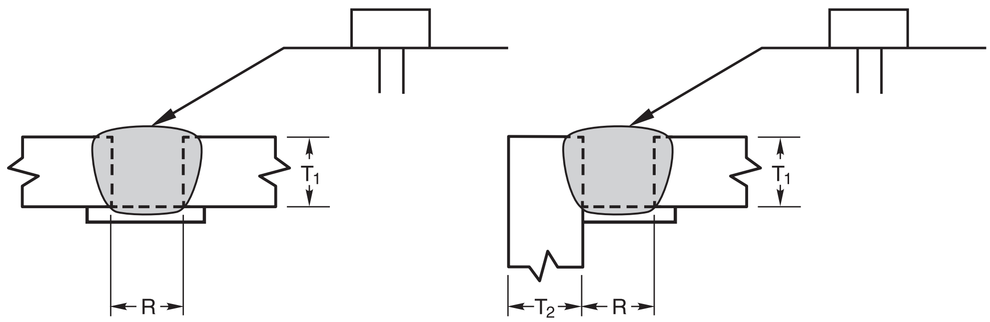
Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
R = +2, –0	+2, –3
α = +10°, –0°	+10°, –5°
f = +2, –0	Not Limited
r = +3, –0	±2

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation				Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening	Groove Angle	Root Face	Groove Radius			
SMAW	TC-U9a	U	U	R = 0 to 3	α = 45°	f = 3	r = 10	All	—	a, c, f, k
				R = 0 to 3	α = 30°	f = 3	r = 10	F, OH	—	c, f, k
GMAW FCAW	TC-U9a-GF	U	U	R = 0 to 3	α = 30°	f = 3	r = 10	All	Not required	c, f, k
SAW	TC-U9a-S	10 min.	10 min.	R = 0	α = 30°	f = 6	r = 10	F	—	c, f, k

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

See Notes on Page 27

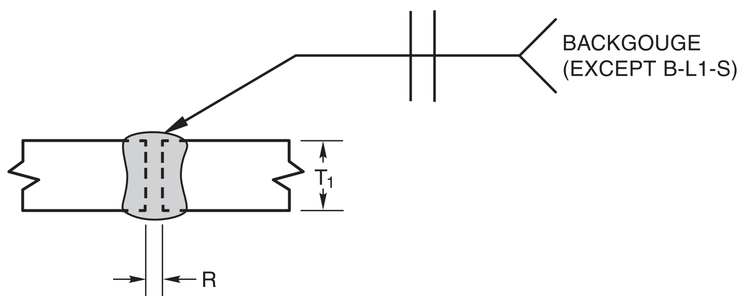
Square-groove weld (1)
Butt joint (B)
Corner joint (C)



B-L1a **C-L1a**

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited) T1	T2	Groove Preparation: Root Opening	Tolerances: As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)	Allowed Welding Positions	Gas Shielding for FCAW	Notes
SMAW	B-L1a	1/4 max.	—	$R = T_1$	+1/16, –0	+1/4, –1/16	All	—	a, h
	C-L1a	1/4 max.	U	$R = T_1$	+1/16, –0	+1/4, –1/16	All	—	h
FCAW GMAW	B-L1a-GF	3/8 max.	—	$R = T_1$	+1/16, –0	+1/4, –1/16	All	Not required	h

Square-groove weld (1)
Butt joint (B)

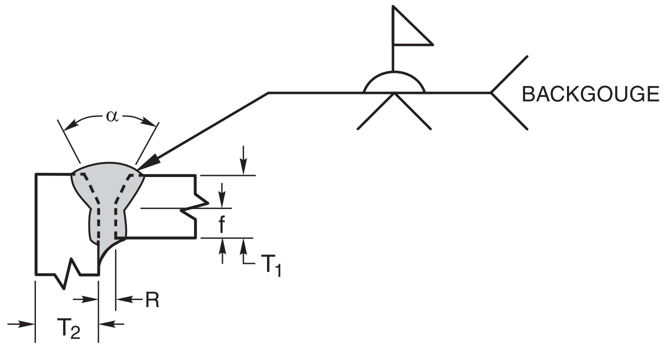


Welding Process	Joint Designation	Base Metal Thickness (U = unlimited) T1	T2	Groove Preparation: Root Opening	Tolerances: As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)	Allowed Welding Positions	Gas Shielding for FCAW	Notes
SMAW	B-L1b	1/4 max.	—	$R = \frac{T_1}{2}$	+1/16, –0	+1/16, –1/8	All	—	a, c, h
GMAW FCAW	B-L1b-GF	3/8 max.	—	R = 0 to 1/8	+1/16, –0	+1/16, –1/8	All	Not required	c, h
SAW	B-L1-S	3/8 max.	—	R = 0	±0	+1/16, –0	F	—	e, h
SAW	B-L1a-S	5/8 max.	—	R = 0	±0	+1/16, –0	F	—	c, h

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

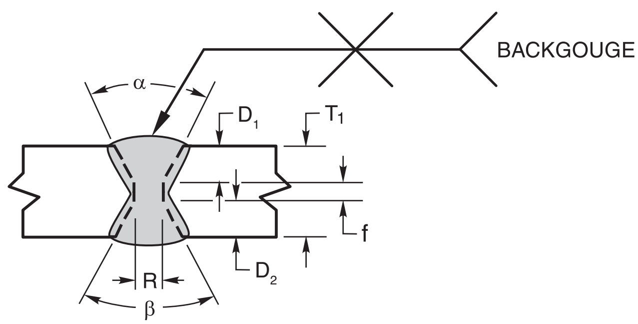
See Notes on Page 27

Single-V-groove weld (2)
Corner joint (C)



Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening Root Face Groove Angle	Tolerances: As Detailed (see 4.12.1)	Tolerances: As Fit-Up (see 5.3.4)			
SMAW	C-U2	U	U	R = 0 to 1/8 f = 0 to 1/8 α = 60°	+1/16, –0 +1/16, –0 +10°, –0°	+1/16, –1/8 Not limited +10°, –5°	All	—	a, c, k
GMAW FCAW	C-U2-GF	U	U	R = 0 to 1/8 f = 0 to 1/8 α = 60°	+1/16, –0 +1/16, –0 +10°, –0°	+1/16, –1/8 Not limited +10°, –5°	All	Not required	c, k
SAW	C-U2b-S	1 min.	U	R = 0 f = 1/4 max. α = 60°	±0 +1/4, –0 +10°, –0°	+1/16, –0 ±1/16 +10°, –5°	F	—	c, k

Double-V-groove weld (3)
Butt joint (B)



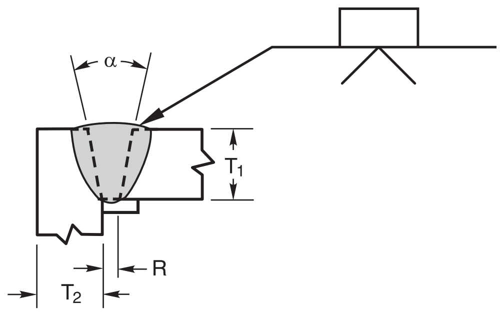
For B-U3c-S only		
T_1		D_1
Over	to	
2	2-1/2	1-3/8
2-1/2	3	1-3/4
3	3-5/8	2-1/8
3-5/8	4	2-1/2
4	4-3/4	2-3/4
4-3/4	5-1/2	3
5-1/2	6-1/4	3-3/4
For $T_1 > 6\text{-}1/4$ or $T_1 \le 2$ $D_1 = 2/3\ (T_1 - 1/4)$		

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening Root Face Groove Angle	Tolerances: As Detailed (see 4.12.1)	Tolerances: As Fit-Up (see 5.3.4)			
SMAW	B-U3b	U	—	R = 0 to 1/8 f = 0 to 1/8 α = β = 60°	+1/16, –0 +1/16, –0 +10°, –0°	+1/16, –1/8 Not limited +10°, –5°	All	—	a, c, f, h
GMAW FCAW	B-U3-GF						All	Not required	c, f, h
SAW	B-U3c-S	U	—	R = 0 f = 1/4 min. α = β = 60° To find D_1 see table above: $D_2 = T_1 - (D_1 + f)$	+1/16, –0 +1/4, –0 +10°, –0°	+1/16, –0 +1/4, –0 +10°, –5°	F	—	c, f, h

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

See Notes on Page 27

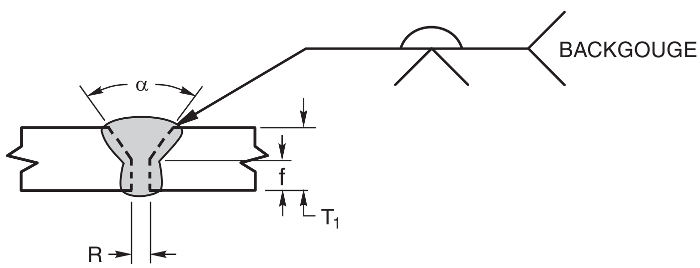
Single-V-groove weld (2)
Corner joint (C)



Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
R = +1/16, –0	+1/4, –1/16
a = +10°, –0°	+10°, –5°

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation		Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening	Groove Angle			
SMAW	C-U2a	U	U	R = 1/4	α = 45°	All	—	a, k
				R = 3/8	α = 30°	F, V, OH	—	a, k
				R = 1/2	α = 20°	F, V, OH	—	a, k
GMAW FCAW	C-U2a-GF	U	U	R = 3/16	α = 30°	F, V, OH	Required	k
				R = 3/8	α = 30°	F, V, OH	Not req.	k
				R = 1/4	α = 45°	F, V, OH	Not req.	k
SAW	C-L2a-S	2 max.	U	R = 1/4	α = 30°	F	—	k
SAW	C-U2-S	U	U	R = 5/8	α = 20°	F	—	k

Single-V-groove weld (2)
Butt joint (B)

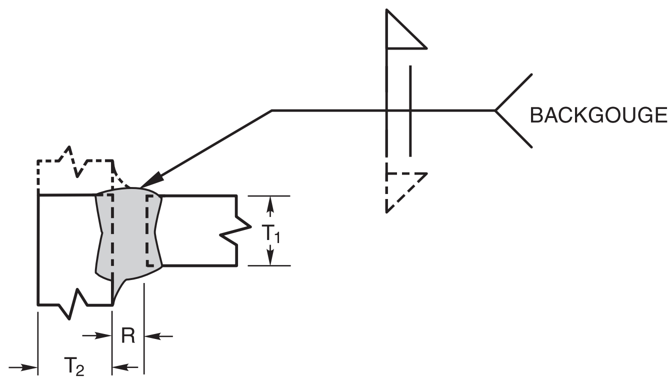


Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Gas Shielding for FCAW	Notes
				Root Opening Root Face Groove Angle	Tolerances				
		T_1	T_2		As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)			
SMAW	B-U2	U	—	R = 0 to 1/8 f = 0 to 1/8 α = 60°	+1/16, –0 +1/16, –0 +10°, –0°	+1/16, –1/8 Not limited +10°, –5°	All	—	a, c, h
GMAW FCAW	B-U2-GF	U	—	R = 0 to 1/8 f = 0 to 1/8 α = 60°	+1/16, –0 +1/16, –0 +10°, –0°	+1/16, –1/8 Not limited +10°, –5°	All	Not required	c, h
SAW	B-L2c-S	Over 1/2 to 1	—	R = 0 f = 1/4 min. α = 60°	R = ±0 f = +1/4, –0 α = +10°, –0°	+1/16, –0 Not limited +10°, –5°	F	—	c, h
		Over 1 to 1-1/2	—	R = 0 f = 3/8 min. α = 60°					
		Over 1-1/2 to 2	—	R = 0 f = 1/2 min. α = 60°					

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

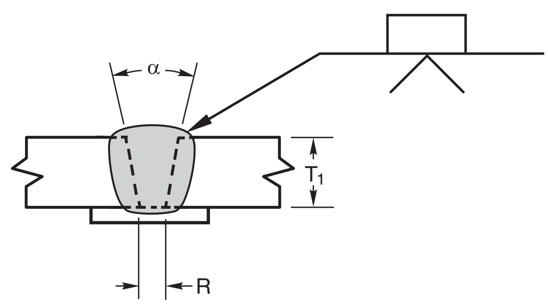
See Notes on Page 27

Square-groove weld (1)
T-joint (T)
Corner joint (C)



Welding Process	Joint Designation	Base Metal Thickness (U = unlimited) T1	T2	Groove Preparation Root Opening	Tolerances As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)	Allowed Welding Positions	Gas Shielding for FCAW	Notes
SMAW	TC-L1b	1/4 max.	U	$R = \frac{T_1}{2}$	+1/16, –0	+1/16, –1/8	All	—	a, c
GMAW FCAW	TC-L1-GF	3/8 max.	U	R = 0 to 1/8	+1/16, –0	+1/16, –1/8	All	Not required	c
SAW	TC-L1-S	3/8 max.	U	R = 0	±0	+1/16, –0	F	—	c

Single-V-groove weld (2)
Butt joint (B)



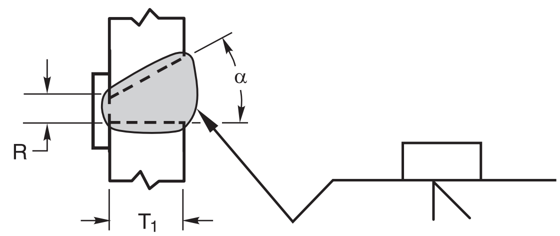
Tolerances	As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
	R = +1/16, –0	+1/4, –1/16
	α = +10°, –0°	+10°, –5°

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited) T1	T2	Groove Preparation Root Opening	Groove Angle	Allowed Welding Positions	Gas Shielding for FCAW	Notes
SMAW	B-U2a	U	—	R = 1/4	α = 45°	All	—	a, h
				R = 3/8	α = 30°	F, V, OH	—	a, h
				R = 1/2	α = 20°	F, V, OH	—	a, h
GMAW FCAW	B-U2a-GF	U	—	R = 3/16	α = 30°	F, V, OH	Required	h
				R = 3/8	α = 30°	F, V, OH	Not req.	h
				R = 1/4	α = 45°	F, V, OH	Not req.	h
SAW	B-L2a-S	2 max.	—	R = 1/4	α = 30°	F	—	h
SAW	B-U2-S	U	—	R = 5/8	α = 20°	F	—	h

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

See Notes on Page 27

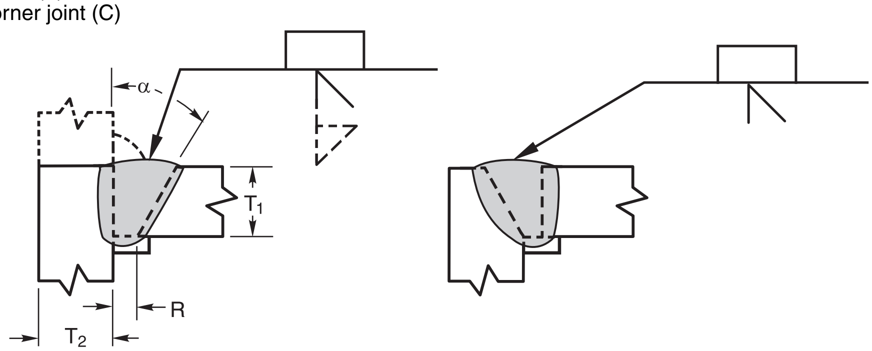
Single-bevel-groove weld (4)
Butt joint (B)



Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
R = +1/16, –0	+1/4, –1/16
a = +10°, –0°	+10°, –5°

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation		Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening	Groove Angle			
SMAW	B-U4a	U	—	R = 1/4	α = 45°	F, H	—	a, h, l
				R = 3/8	α = 30°	F, H	—	a, h, l
GMAW FCAW	B-U4a-GF	U	—	R = 3/16	α = 30°	H	Required	h
				R = 1/4	α = 45°	H	Not req.	h
				R = 3/8	α = 30°	H	Not req.	h

Single-bevel-groove weld (4)
T-joint (T)
Corner joint (C)



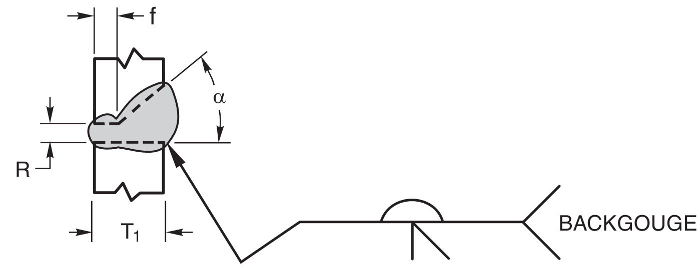
Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
R = +1/16, –0	+1/4, –1/16
α = +10°, –0°	+10°, –5°

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation		Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening	Groove Angle			
SMAW	TC-U4a	U	U	R = 1/4	α = 45°	All	—	a, k
				R = 3/8	α = 30°	F, OH, H	—	a, k
GMAW FCAW	TC-U4a-GF	U	U	R = 3/16	α = 30°	All	Required	k
				R = 3/8	α = 30°	F	Not req.	k
				R = 1/4	α = 45°	All	Not req.	k
SAW	TC-U4a-S	U	U	R = 3/8	α = 30°	F	—	k
				R = 1/4	α = 45°			

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

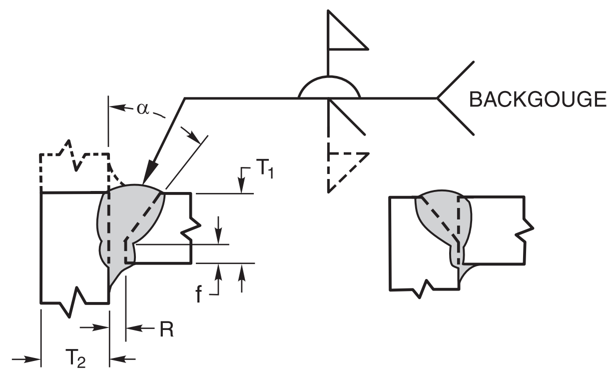
See Notes on Page 27

Single-bevel-groove weld (4)
Butt joint (B)



Welding Process	Joint Designation	Base Metal Thickness (U = unlimited) T_1	T_2	Groove Preparation: Root Opening	Tolerances: As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)	Allowed Welding Positions	Gas Shielding for FCAW	Notes
SMAW	B-U4b	U	—	R = 0 to 1/8 f = 0 to 1/8 α = 45°	+1/16, –0 +1/16, –0 +10°, –0°	+1/16, –1/8 Not limited 10°, –5°	F, H	—	a, c, h, l
GMAW FCAW	B-U4b-GF	U	—				H	Not required	c, h

Single-bevel-groove weld (4)
T-joint (T)
Corner joint (C)

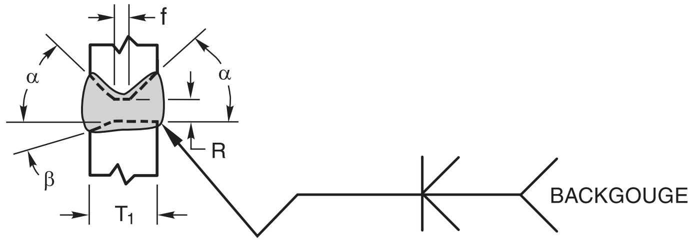


Welding Process	Joint Designation	Base Metal Thickness (U = unlimited) T_1	T_2	Groove Preparation: Root Opening Root Face Groove Angle	Tolerances: As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)	Allowed Welding Positions	Gas Shielding for FCAW	Notes
SMAW	TC-U4b	U	U	R = 0 to 1/8 f = 0 to 1/8 α = 45°	+1/16, –0 +1/16, –0 +10°, –0°	+1/16, –1/8 Not limited 10°, –5°	All	—	a, c, k
GMAW FCAW	TC-U4b-GF	U	U				All	Not required	c, k
SAW	TC-U4b-S	U	U	R = 0 f = 1/4 max. α = 60°	±0 +0, –1/8 +10°, –0°	+1/4, –0 ±1/16 10°, –5°	F	—	c, k

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

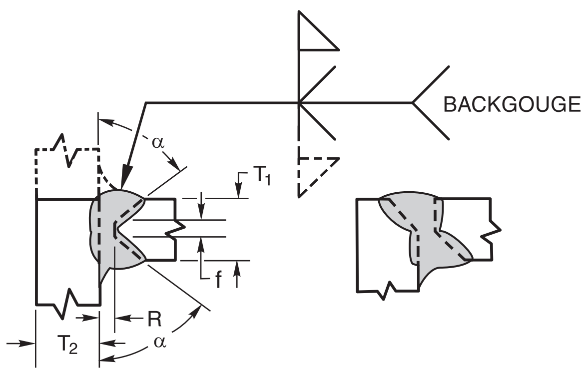
See Notes on Page 27

Double-bevel-groove weld (5)
Butt joint (B)



Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Gas Shielding for FCAW	Notes
				Root Opening Root Face Groove Angle	Tolerances				
		T_1	T_2		As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)			
SMAW	B-U5a	U	—	R = 0 to 1/8 f = 0 to 1/8 α = 45° β = 0° to 15°	+1/16, –0 +1/16, –0 α + β +10° –0°	+1/16, –1/8 Not limited α + β +10° –5°	F, H	—	a, c, f, h, l
GMAW FCAW	B-U5-GF	U	—	R = 0 to 1/8 f = 0 to 1/8 α = 45° β = 0° to 15°	+1/16, –0 +1/16, –0 α + β = +10°, –0°	+1/16, –1/8 Not limited α + β = +10°, –5°	H	Not required	c, f, h

Double-bevel-groove weld (5)
T-joint (T)
Corner joint (C)

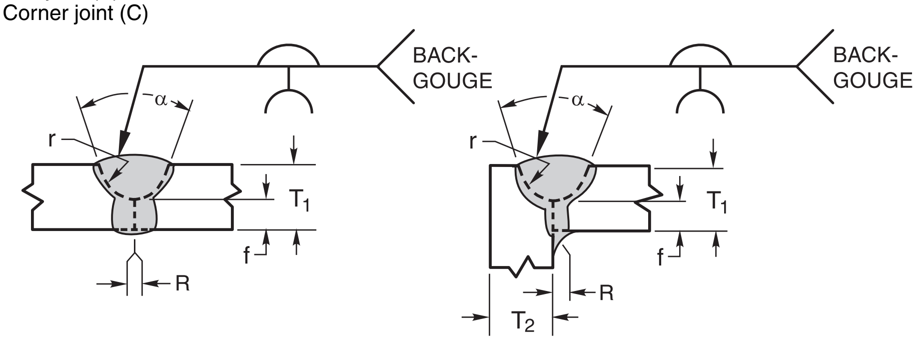


Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Gas Shielding for FCAW	Notes
				Root Opening Root Face Groove Angle	Tolerances				
		T_1	T_2		As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)			
SMAW	TC-U5b	U	U	R = 0 to 1/8 f = 0 to 1/8 α = 45°	+1/16, –0 +1/16, –0 +10°, –0°	+1/16, –1/8 Not limited +10°, –5°	All	—	a, c, f, k
GMAW FCAW	TC-U5-GF	U	U				All	Not required	c, f, k
SAW	TC-U5-S	U	U	R = 0 f = 3/16 max. α = 60°	±0 +0, –3/16 +10°, –0°	+1/16, –0 ±1/16 +10°, –5°	F	—	c, f, k

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

See Notes on Page 27

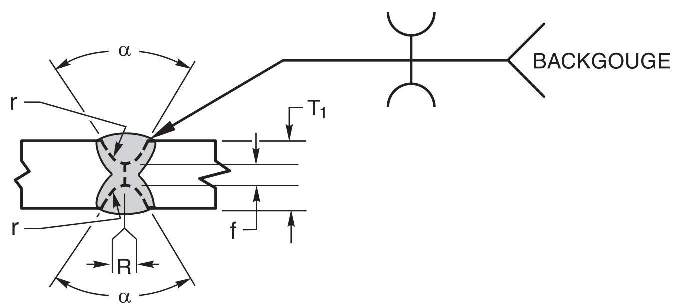
Single-U-groove weld (6)
Butt joint (B)
Corner joint (C)



Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
R = +1/16, –0	+1/16, –1/8
α = +10°, –0°	+10°, –5°
f = ±1/16	Not Limited
r = +1/8, –0	+1/8, –0

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited) T_1	T_2	Groove Preparation Root Opening	Groove Angle	Root Face	Groove Radius	Allowed Welding Positions	Gas Shielding for FCAW	Notes
SMAW	B-U6	U	U	R = 0 to 1/8	α = 45°	f = 1/8	r = 1/4	All	—	a, c, h
				R = 0 to 1/8	α = 20°	f = 1/8	r = 1/4	F, OH	—	a, c, h
	C-U6	U	U	R = 0 to 1/8	α = 45°	f = 1/8	r = 1/4	All	—	a, c, k
				R = 0 to 1/8	α = 20°	f = 1/8	r = 1/4	F, OH	—	a, c, k
GMAW FCAW	B-U6-GF	U	U	R = 0 to 1/8	α = 20°	f = 1/8	r = 1/4	All	Not req.	c, h
	C-U6-GF	U	U	R = 0 to 1/8	α = 20°	f = 1/8	r = 1/4	All	Not req.	c, k
SAW	B-U6-S	5/8 min.	5/8 min.	R = 0	α = 20°	f = 1/4 min.	r = 1/4	F	—	c, h
	C-U6-S	5/8 min.	5/8 min.	R = 0	α = 20°	f = 1/4 min.	r = 1/4	F	—	c, k

Double-U-groove weld (7)
Butt joint (B)



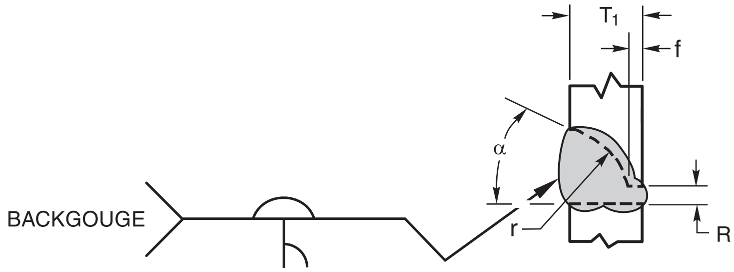
Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
For B-U7 and B-U7-GF	
R = +1/16, –0	+1/16, –1/8
α = +10°, –0°	+10°, –5°
f = ±1/16, –0	Not Limited
r = +1/4, –0	±1/16
For B-U7-S	
R = ±0	+1/16, –0
f = +0, –1/4	±1/16

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited) T_1	T_2	Groove Preparation Root Opening	Groove Angle	Root Face	Groove Radius	Allowed Welding Positions	Gas Shielding for FCAW	Notes
SMAW	B-U7	U	—	R = 0 to 1/8	α = 45°	f = 1/8	r = 1/4	All	—	a, c, f, h
				R = 0 to 1/8	α = 20°	f = 1/8	r = 1/4	F, OH	—	a, c, f, h
GMAW FCAW	B-U7-GF	U	—	R = 0 to 1/8	α = 20°	f = 1/8	r = 1/4	All	Not required	c, f, h
SAW	B-U7-S	U	—	R = 0	α = 20°	f = 1/4 max.	r = 1/4	F	—	c, f, h

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

See Notes on Page 27

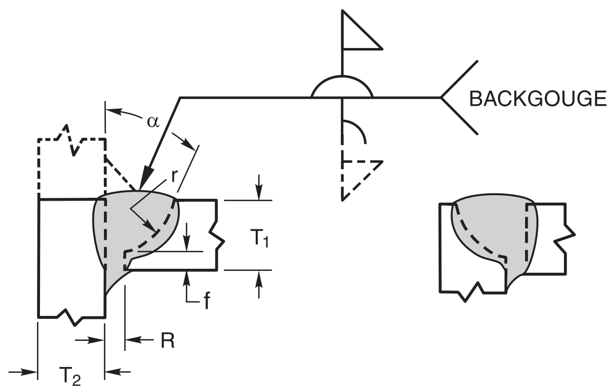
Single-J-groove weld (8)
Butt joint (B)



Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
R = +1/16, –0	+1/16, –1/8
α = +10°, –0°	+10°, –5°
f = +1/16, –0	Not Limited
r = +1/4, –0	±1/16

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation				Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening	Groove Angle	Root Face	Groove Radius			
SMAW	B-U8	U	—	R = 0 to 1/8	α = 45°	f = 1/8	r = 3/8	F, H	—	a, c, h, l
GMAW FCAW	B-U8-GF	U	—	R = 0 to 1/8	α = 30°	f = 1/8	r = 3/8	H	Not required	c, h

Single-J-groove weld (8)
T-joint (T)
Corner joint (C)



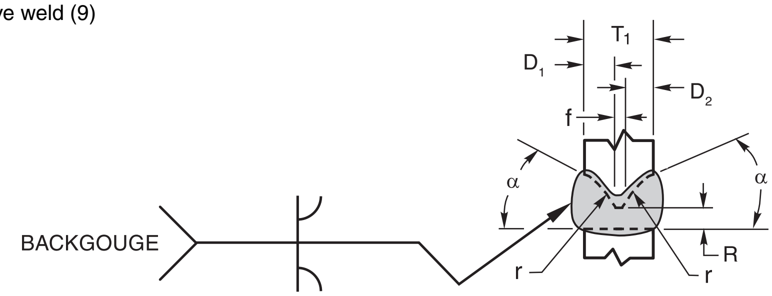
Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
R = +1/16, –0	+1/16, –1/8
α = +10°, –0°	+10°, –5°
f = +1/16, –0	Not Limited
r = +1/4, –0	±1/16

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation				Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening	Groove Angle	Root Face	Groove Radius			
SMAW	TC-U8a	U	U	R = 0 to 1/8	α = 45°	f = 1/8	r = 3/8	All	—	a, c, h
				R = 0 to 1/8	α = 30°	f = 1/8	r = 3/8	F, OH	—	a, c, h
GMAW FCAW	TC-U8a-GF	U	U	R = 0 to 1/8	α = 30°	f = 1/8	r = 3/8	All	Not required	c, h
SAW	TC-U8a-S	5/8 min.	5/8 min.	R = 0	α = 30°	f = 1/4 min.	r = 3/8	F	—	c, h

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

See Notes on Page 27

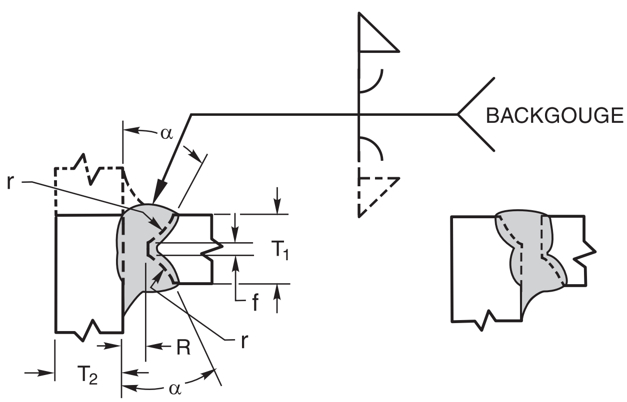
Double-J-groove weld (9)
Butt joint (B)



Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
R = +1/16, –0	+1/16, –1/8
α = +10°, –0°	+10°, –5°
f = +1/16, –0	Not Limited
r = +1/8, –0	±1/16

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation				Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening	Groove Angle	Root Face	Groove Radius			
SMAW	B-U9	U	—	R = 0 to 1/8	α = 45°	f = 1/8	r = 3/8	F, H	—	a, c, f, h, l
GMAW FCAW	B-U9-GF	U	—	R = 0 to 1/8	α = 30°	f = 1/8	r = 3/8	H	Not required	c, f, h

Double-J-groove weld (9)
T-joint (T)
Corner joint (C)



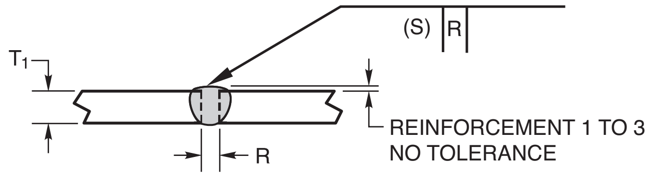
Tolerances	
As Detailed (see 4.12.1)	As Fit-Up (see 5.3.4)
R = +1/16, –0	+1/16, –1/8
α = +10°, –0°	+10°, –5°
f = +1/16, –0	Not Limited
r = +1/8, –0	±1/16

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation				Allowed Welding Positions	Gas Shielding for FCAW	Notes
		T_1	T_2	Root Opening	Groove Angle	Root Face	Groove Radius			
SMAW	TC-U9a	U	U	R = 0 to 1/8	α = 45°	f = 1/8	r = 3/8	All	—	a, c, f, k
				R = 0 to 1/8	α = 30°	f = 1/8	r = 3/8	F, OH	—	c, f, k
GMAW FCAW	TC-U9a-GF	U	U	R = 0 to 1/8	α = 30°	f = 1/8	r = 3/8	All	Not required	c, f, k
SAW	TC-U9a-S	3/8 min.	3/8 min.	R = 0	α = 30°	f = 1/4	r = 3/8	F	—	c, f, k

Figure 4.4 (Continued)—Details of Welded Joints for CJP Groove Welds (see 4.12.1) (Dimensions in Millimeters)

See Notes on Page 27

Square-groove weld (1)
Butt joint (B)

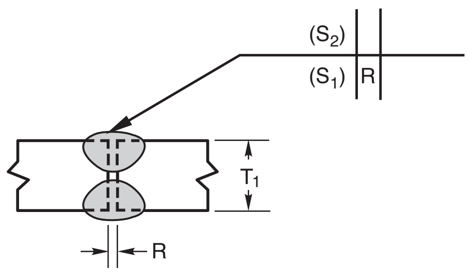


FOR BUTT JOINT RESTRICTIONS, SEE 4.14

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Weld Size (S)	Notes
		T_1	T_2	Root Opening	Tolerances: As Detailed (see 4.13.1)	Tolerances: As Fit-Up (see 5.3.4)			
SMAW	B-P1a	3 max.	—	R = 0 to 2	+2, –0	±2	All	$T_1 - 1$	a, b
	B-P1c	6 max.	—	$R = \frac{T_1}{2}$ min.	+2, –0	±2	All	$\frac{T_1}{2}$	a, b

Square-groove weld (1)
Butt joint (B)

$S_1 + S_2$ MUST NOT EXCEED $\frac{3T_1}{4}$



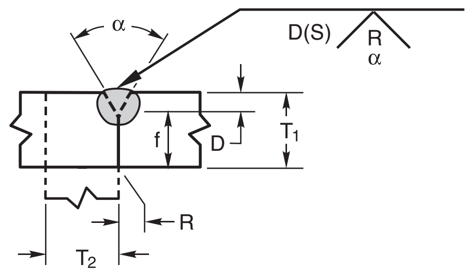
FOR BUTT JOINT RESTRICTIONS, SEE 4.14

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Total Weld Size ($S_1 + S_2$)	Notes
		T_1	T_2	Root Opening	Tolerances: As Detailed (see 4.13.1)	Tolerances: As Fit-Up (see 5.3.4)			
SMAW	B-P1b	6 max.	—	$R = \frac{T_1}{2}$	+2, –0	±2	All	$\frac{3T_1}{4}$	a

Figure 4.5—Details of Welded Joints for PJP Groove Welds (see 4.13.1) (Dimensions in Millimeters)

See Notes on Page 27

Single-V-groove weld (2)
Corner joint (C)

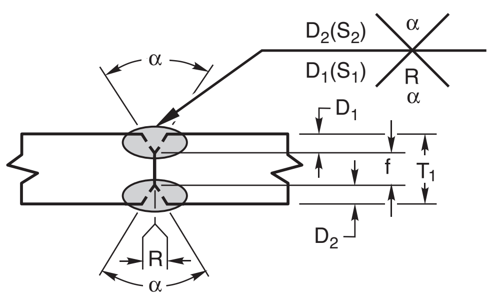


FOR BUTT JOINT RESTRICTIONS, SEE 4.14

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Weld Size (S)	Notes
		T_1	T_2	Root Opening Root Face Groove Angle	Tolerances: As Detailed (see 4.13.1)	Tolerances: As Fit-Up (see 5.3.4)			
SMAW	C-P2	6 min.	U	R = 0 f = 1 min. α = 60°	+2, –0 Unlimited +10°, –0°	+3, –2 ±2 +10°, –5°	All	E	a, b, d, j
GMAW FCAW	C-P2-GF	6 min.	U	R = 0 f = 3 min. α = 60°	+2, –0 Unlimited +10°, –0°	+3, –2 ±2 +10°, –5°	All	E	b, d, j
SAW	C-P2-S	11 min.	U	R = 0 f = 6 min. α = 60°	±0 Unlimited +10°, –0°	+2, –0‡ ±2 +10°, –5°	F	E	b, d, j

‡Fit-up tolerance, see 5.3.2, for rolled shapes R may be 8 mm in thick plates if backing is provided.

Double-V-groove weld (3)
Butt joint (B)



FOR BUTT JOINT RESTRICTIONS, SEE 4.14

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Total Weld Size ($S_1 + S_2$)	Notes
		T_1	T_2	Root Opening Root Face Groove Angle	Tolerances: As Detailed (see 4.13.1)	Tolerances: As Fit-Up (see 5.3.4)			
SMAW	B-P3	12 min.	—	R = 0 f = 3 min. α = 60°	+2, –0 Unlimited +10°, –0°	+3, –2 ±2 +10°, –5°	All	$D_1 + D_2$	a, d, g, j
GMAW FCAW	B-P3-GF	12 min.	—	R = 0 f = 3 min. α = 60°	+2, –0 Unlimited +10°, –0°	+3, –2 ±2 +10°, –5°	All	$D_1 + D_2$	d, g, j
SAW	B-P3-S	20 min.	—	R = 0 f = 6 min. α = 60°	±0 Unlimited +10°, –0°	+2, –0 ±2 +10°, –5°	F	$D_1 + D_2$	d, g, j

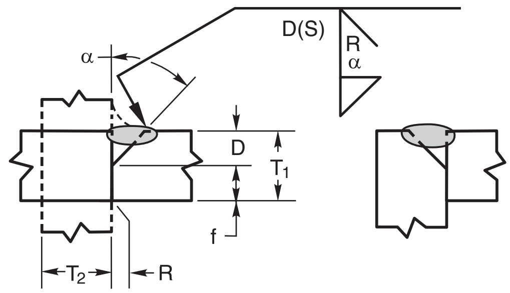
Figure 4.5 (Continued)—Details of Welded Joints for PJP Groove Welds (see 4.13.1) (Dimensions in Millimeters)

See Notes on Page 27

Single-bevel-groove (4)
T-joint (T)
Corner joint (C)

FOR CORNER AND T-JOINT RESTRICTIONS, SEE 4.11

FOR BUTT JOINT RESTRICTIONS, SEE 4.14



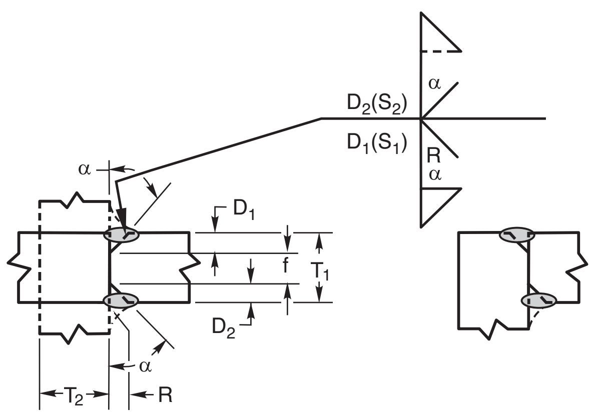
Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Weld Size (S)	Notes
		T_1	T_2	Root Opening Root Face Groove Angle	Tolerances: As Detailed (see 4.13.1)	Tolerances: As Fit-Up (see 5.3.4)			
SMAW	TC-P4	U	U	R = 0 f = 3 min. α = 45°	+2, –0 Unlimited +10°, –0°	+3, –2 ±2 +10°, –5°	All	D–3	a, b, d, j
GMAW FCAW	TC-P4-GF	6 min.	U	R = 0 f = 3 min. α = 45°	+2, –0 Unlimited +10°, –0°	+3, –2 ±2 +10°, –5°	All	D–3	b, d, j
SAW	TC-P4-S	11 min.	U	R = 0 f = 6 min. α = 60°	±0 Unlimited +10°, –0°	+2, –0‡ ±2 +10°, –5°	F	D	b, d, j

‡Fit-up tolerance, see 5.3.2, for rolled shapes R may be 8 mm in thick plates if backing is provided.

Double-bevel-groove weld (5)
T-joint (T)
Corner joint (C)

FOR CORNER AND T-JOINT RESTRICTIONS, SEE 4.11

FOR BUTT JOINT RESTRICTIONS, SEE 4.14



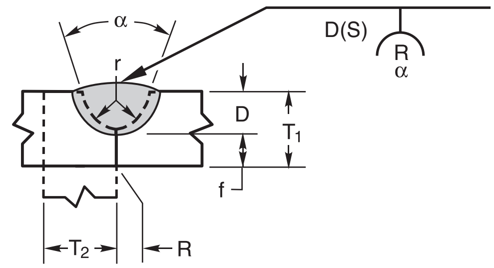
Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Total Weld Size ($S_1 + S_2$)	Notes
		T_1	T_2	Root Opening Root Face Groove Angle	Tolerances: As Detailed (see 4.13.1)	Tolerances: As Fit-Up (see 5.3.4)			
SMAW	TC-P5	8 min.	U	R = 0 f = 3 min. α = 45°	+2, –0 Unlimited +10°, –0°	+3, –2 ±2 +10°, –5°	All	$(D_1 + D_2)$ –6	a, d, g, j
GMAW FCAW	TC-P5-GF	12 min.	U	R = 0 f = 3 min. α = 45°	+2, –0 Unlimited +10°, –0°	+3, –2 ±2 +10°, –5°	All	$(D_1 + D_2)$ –6	d, g, j
SAW	TC-P5-S	20 min.	U	R = 0 f = 6 min. α = 60°	±0 Unlimited +10°, –0°	+2, –0 ±2 +10°, –5°	F	$D_1 + D_2$	d, g, j

‡Fit-up tolerance, see 5.3.2, for rolled shapes R may be 8 mm in thick plates if backing is provided.

Figure 4.5 (Continued)—Details of Welded Joints for PJP Groove Welds (see 4.13.1) (Dimensions in Millimeters)

See Notes on Page 27

Single-U-groove weld (6)
Corner joint (C)



FOR CORNER AND T-JOINT RESTRICTIONS, SEE 4.11

FOR BUTT JOINT RESTRICTIONS, SEE 4.14

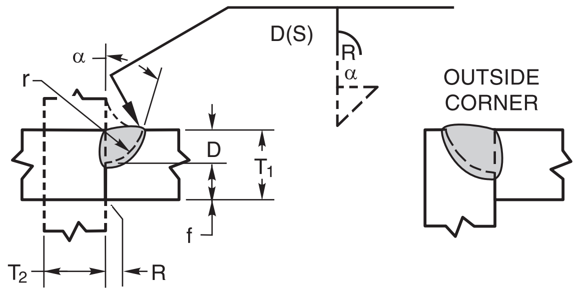
Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Weld Size (E)	Notes
				Root Opening Root Face Groove Radius Groove Angle	Tolerances				
		T_1	T_2		As Detailed (see 4.13.1)	As Fit-Up (see 5.3.4)			
SMAW	C-P6	6 min.	U	R = 0 f = 1 min. r = 6 α = 45°	+2, –0 +U, –0 +6, –0 +10°, –0°	+3, –2 ±2 ±2 +10°, –5°	All	S	a, b, d, j
GMAW FCAW	C-P6-GF	6 min.	U	R = 0 f = 3 min. r = 6 α = 20°	+2, –0 +U, –0 +6, –0 +10°, –0°	+3, –2 ±2 ±2 +10°, –5°	All	S	b, d, j
SAW	C-P6-S	11 min.	U	R = 0 f = 6 min. r = 6 α = 20°	±0 +U, –0 +6, –0 +10°, –0°	+2, –0‡ ±2 ±2 +10°, –5°	F	S	b, d, j

‡Fit-up tolerance, see 5.3.2, for rolled shapes R may be 8 mm in thick plates if backing is provided.

Figure 4.5 (Continued)—Details of Welded Joints for PJP Groove Welds (see 4.13.1) (Dimensions in Millimeters)

See Notes on Page 27

Single-J-groove weld (8)
T-joint (T)
Corner joint (C)



FOR CORNER AND T-JOINT RESTRICTIONS, SEE 4.11

FOR BUTT JOINT RESTRICTIONS, SEE 4.14

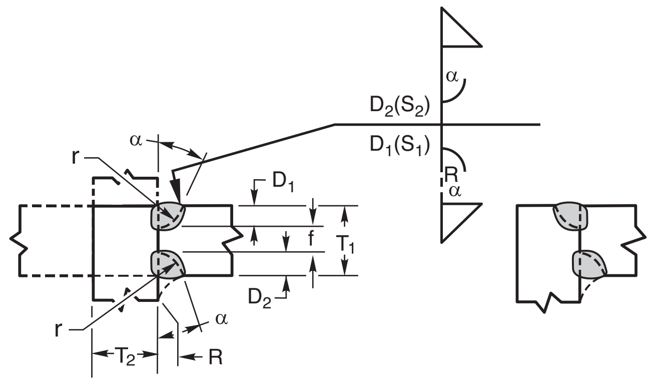
Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Weld Size (S)	Notes
				Root Opening Root Face Groove Radius Groove Angle	Tolerances				
		T_1	T_2		As Detailed (see 4.13.1)	As Fit-Up (see 5.3.4)			
SMAW	TC-P8	6 min.	U	R = 0 f = 3 min. r = 10 α = 45°	+2, –0 Not limited +6, –0 +10°, –0°	+3, –2 ±2 ±2 +10°, –5°	All	D	a, d, j
SMAW	C-P8*	6 min.	U	R = 0 f = 3 min. r = 10 α = 30°	+2, –0 Not limited +6, –0 +10°, –0°	+3, –2 ±2 ±2 +10°, –5°	All	D	a, d, j
GMAW FCAW	TC-P8-GF	6 min.	U	R = 0 f = 3 min. r = 10 α = 45°	+2, –0 Not limited +6, –0 +10°, –0°	+3, –2 ±2 ±2 +10°, –5°	All	D	d, j
GMAW FCAW	C-P8-GF*	6 min.	U	R = 0 f = 3 min. r = 10 α = 30°	+2, –0 Not limited +6, –0 +10°, –0°	+3, –2 ±2 ±2 +10°, –5°	All	D	d, j
SAW	TC-P8-S	11 min.	U	R = 0 f = 6 min. r = 12 α = 45°	±0 Not limited +6, –0 +10°, –0°	+2, –0‡ ±2 ±2 +10°, –5°	F	D	d, j
SAW	C-P8-S*	11 min.	U	R = 0 f = 6 min. r = 12 α = 30°	±0 Not limited +6, –0 +10°, –0°	+2, –0‡ ±2 ±2 +10°, –5°	F	D	d, j

‡Fit-up tolerance, see 5.3.2, for rolled shapes R may be 8 mm in thick plates if backing is provided.
*Applies to outside corner joints.

Figure 4.5 (Continued)—Details of Welded Joints for PJP Groove Welds (see 4.13.1) (Dimensions in Millimeters)

See Notes on Page 27

Double-J-groove weld (9)
T-joint (T)
Corner joint (C)



FOR CORNER AND T-JOINT RESTRICTIONS, SEE 4.11

FOR BUTT JOINT RESTRICTIONS, SEE 4.14

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited) T1	T2	Groove Preparation: Root Opening Root Face Groove Radius Groove Angle	Tolerances: As Detailed (see 4.13.1)	As Fit-Up (see 5.3.4)	Allowed Welding Positions	Total Weld Size ($S_1 + S_2$)	Notes
SMAW	TC-P9	12 min.	U	R = 0 f = 3 min. r = 10 α = 45°	+2, –0 –0 +6, –0 +10°, –0°	+3, –2 ±2 ±2 +10°, –5°	All	$D_1 + D_2$	a, d, g, j
GMAW FCAW	TC-P9-GF*	12 min.	U	R = 0 f = 3 min. r = 10 α = 30°	+2, –0 Not limited +6, –0 +10°, –0°	+3, –2 ±2 ±2 +10°, –5°	All	$D_1 + D_2$	d, g, j
SAW	C-P9-S	20 min.	U	R = 0 f = 6 min. r = 12 α = 45°	±0 Not limited +6, –0 +10°, –0°	+2, –0 ±2 ±2 +10°, –5°	F	$D_1 + D_2$	d, g, j
SAW	C-P9-S*	20 min.	U	R = 0 f = 6 min. r = 12 α = 20°	±0 Not limited +6, –0 +10°, –0°	+2, –0‡ ±2 ±2 +10°, –5°	F	$D_1 + D_2$	d, g, j
SAW	T-P9-S	20 min.	U	R = 0 f = 6 min. r = 12 α = 45°	±0 Not limited +6, –0 +10°, –0°	+2, –0‡ ±2 ±2 +10°, –5°	F	$D_1 + D_2$	d, g, j

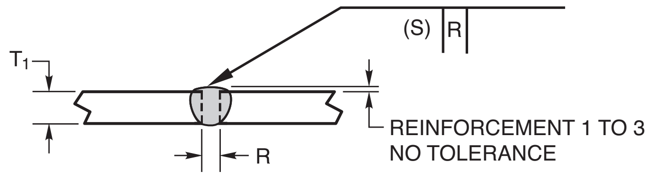
‡Fit-up tolerance, see 5.3.2, for rolled shapes R may be 8 mm in thick plates if backing is provided.
*Applies to outside corner joints.

Figure 4.5 (Continued)—Details of Welded Joints for PJP Groove Welds (see 4.13.1) (Dimensions in Millimeters)

See Notes on Page 27

Square-groove weld (1)
Butt joint (B)

FOR BUTT JOINT RESTRICTIONS, SEE 4.14

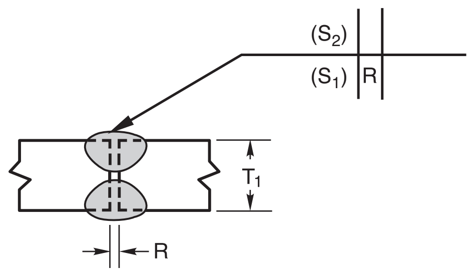


Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Weld Size (S)	Notes
					Tolerances				
		T_1	T_2	Root Opening	As Detailed (see 4.13.1)	As Fit-Up (see 5.3.4)			
SMAW	B-P1a	1/8 max.	—	R = 0 to 1/16	+1/16, –0	±1/16	All	$T_1 - 1/32$	a, b
	B-P1c	1/4 max.	—	$R = \frac{T_1}{2}$ min.	+1/16, –0	±1/16	All	$\frac{T_1}{2}$	a, b

Square-groove weld (1)
Butt joint (B)

$S_1 + S_2$ MUST NOT EXCEED $\frac{3T_1}{4}$

FOR BUTT JOINT RESTRICTIONS, SEE 4.14

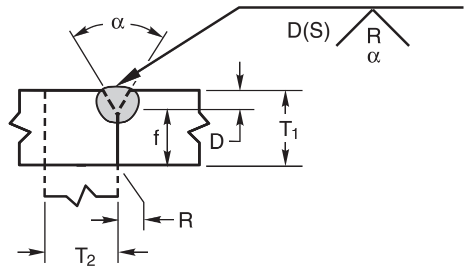


Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Total Weld Size ($S_1 + S_2$)	Notes
					Tolerances				
		T_1	T_2	Root Opening	As Detailed (see 4.13.1)	As Fit-Up (see 5.3.4)			
SMAW	B-P1b	1/4 max.	—	$R = \frac{T_1}{2}$	+1/16, –0	±1/16	All	$\frac{3T_1}{4}$	a

Figure 4.5 (Continued)—Details of Welded Joints for PJP Groove Welds (see 4.13.1) (Dimensions in Inches)

See Notes on Page 27

Single-V-groove weld (2)
Corner joint (C)

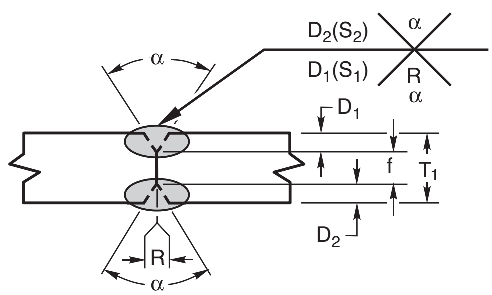


FOR BUTT JOINT RESTRICTIONS, SEE 4.14

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Weld Size (S)	Notes
		T_1	T_2	Root Opening Root Face Groove Angle	Tolerances: As Detailed (see 4.13.1)	Tolerances: As Fit-Up (see 5.3.4)			
SMAW	C-P2	1/4 min.	U	R = 0 f = 1/32 min. α = 60°	+1/16, –0 Unlimited +10°, –0°	+1/8, –1/16 ±1/16 +10°, –5°	All	D	a, b, d, j
GMAW FCAW	C-P2-GF	1/4 min.	U	R = 0 f = 1/8 min. α = 60°	+1/16, –0 Unlimited +10°, –0°	+1/8, –1/16 ±1/16 +10°, –5°	All	D	b, d, j
SAW	C-P2-S	7/16 min.	U	R = 0 f = 1/4 min. α = 60°	±0 Unlimited +10°, –0°	+1/16, –0‡ ±1/16 +10°, –5°	F	D	b, d, j

‡Fit-up tolerance, see 5.3.2, for rolled shapes R may be 5/16 in in thick plates if backing is provided.

Double-V-groove weld (3)
Butt joint (B)



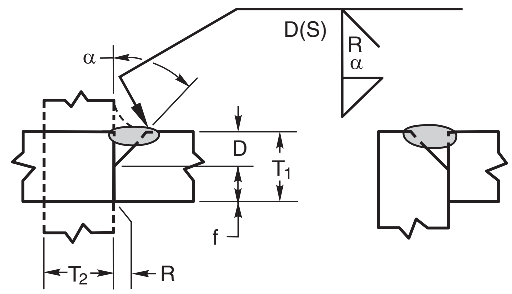
FOR BUTT JOINT RESTRICTIONS, SEE 4.14

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Total Weld Size ($S_1 + S_2$)	Notes
		T_1	T_2	Root Opening Root Face Groove Angle	Tolerances: As Detailed (see 4.13.1)	Tolerances: As Fit-Up (see 5.3.4)			
SMAW	B-P3	1/2 min.	—	R = 0 f = 1/8 min. α = 60°	+1/16, –0 Unlimited +10°, –0°	+1/8, –1/16 ±1/16 +10°, –5°	All	$D_1 + D_2$	a, d, g, j
GMAW FCAW	B-P3-GF	1/2 min.	—	R = 0 f = 1/8 min. α = 60°	+1/16, –0 Unlimited +10°, –0°	+1/8, –1/16 ±1/16 +10°, –5°	All	$D_1 + D_2$	d, g, j
SAW	B-P3-S	3/4 min.	—	R = 0 f = 1/4 min. α = 60°	±0 Unlimited +10°, –0°	+1/16, –0 ±1/16 +10°, –5°	F	$D_1 + D_2$	d, g, j

Figure 4.5 (Continued)—Details of Welded Joints for PJP Groove Welds (see 4.13.1) (Dimensions in Inches)

See Notes on Page 27

Single-bevel-groove (4)
T-joint (T)
Corner joint (C)



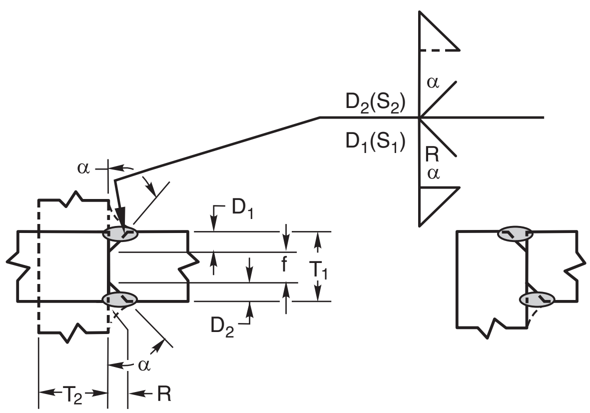
FOR CORNER AND T-JOINT RESTRICTIONS, SEE 4.11

FOR BUTT JOINT RESTRICTIONS, SEE 4.14

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Weld Size (S)	Notes
				Root Opening Root Face Groove Angle	Tolerances				
		T_1	T_2		As Detailed (see 4.13.1)	As Fit-Up (see 5.3.4)			
SMAW	TC-P4	U	U	R = 0 f = 1/8 min. α = 45°	+1/16, –0 Unlimited +10°, –0°	+1/8, –1/16 ±1/16 +10°, –5°	All	D–1/8	a, b, d, j
GMAW FCAW	TC-P4-GF	1/4 min.	U	R = 0 f = 1/8 min. α = 45°	+1/16, –0 Unlimited +10°, –0°	+1/8, –1/16 ±1/16 +10°, –5°	All	D–1/8	b, d, j
SAW	TC-P4-S	7/16 min.	U	R = 0 f = 1/4 min. α = 60°	±0 Unlimited +10°, –0°	+1/16, –0‡ ±1/16 +10°, –5°	F	D	b, d, j

‡Fit-up tolerance, see 5.3.2, for rolled shapes R may be 5/16 in in thick plates if backing is provided.

Double-bevel-groove weld (5)
T-joint (T)
Corner joint (C)



FOR CORNER AND T-JOINT RESTRICTIONS, SEE 4.11

FOR BUTT JOINT RESTRICTIONS, SEE 4.14

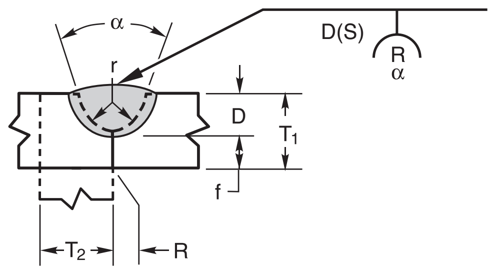
Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Total Weld Size ($S_1 + S_2$)	Notes
				Root Opening Root Face Groove Angle	Tolerances				
		T_1	T_2		As Detailed (see 4.13.1)	As Fit-Up (see 5.3.4)			
SMAW	TC-P5	5/16 min.	U	R = 0 f = 1/8 min. α = 45°	+1/16, –0 Unlimited +10°, –0°	+1/8, –1/16 ±1/16 +10°, –5°	All	($D_1 + D_2$) –1/4	a, d, g, j
GMAW FCAW	TC-P5-GF	1/2 min.	U	R = 0 f = 1/8 min. α = 45°	+1/16, –0 Unlimited +10°, –0°	+1/8, –1/16 ±1/16 +10°, –5°	All	($D_1 + D_2$) –1/4	d, g, j
SAW	TC-P5-S	3/4 min.	U	R = 0 f = 1/4 min. α = 60°	±0 Unlimited +10°, –0°	+1/16, –0 ±1/16 +10°, –5°	F	$D_1 + D_2$	d, g, j

‡Fit-up tolerance, see 5.3.2, for rolled shapes R may be 5/16 in in thick plates if backing is provided.

Figure 4.5 (Continued)—Details of Welded Joints for PJP Groove Welds (see 4.13.1) (Dimensions in Inches)

See Notes on Page 27

Single-U-groove weld (6)
Corner joint (C)



FOR CORNER AND T-JOINT RESTRICTIONS, SEE 4.11

FOR BUTT JOINT RESTRICTIONS, SEE 4.14

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Weld Size (S)	Notes
				Root Opening Root Face Groove Radius Groove Angle	Tolerances				
		T_1	T_2		As Detailed (see 4.13.1)	As Fit-Up (see 5.3.4)			
SMAW	C-P6	1/4 min.	U	R = 0 f = 1/32 min. r = 1/4 α = 45°	+1/16, –0 +U, –0 +1/4, –0 +10°, –0°	+1/8, –1/16 ±1/16 ±1/16 +10°, –5°	All	D	a, b, d, j
GMAW FCAW	C-P6-GF	1/4 min.	U	R = 0 f = 1/8 min. r = 1/4 α = 20°	+1/16, –0 +U, –0 +1/4, –0 +10°, –0°	+1/8, –1/16 ±1/16 ±1/16 +10°, –5°	All	D	b, d, j
SAW	C-P6-S	7/16 min.	U	R = 0 f = 1/4 min. r = 1/4 α = 20°	±0 +U, –0 +1/4, –0 +10°, –0°	+1/16, –0‡ ±1/16 ±1/16 +10°, –5°	F	D	b, d, j

‡Fit-up tolerance, see 5.3.2, for rolled shapes R may be 5/16 in in thick plates if backing is provided.

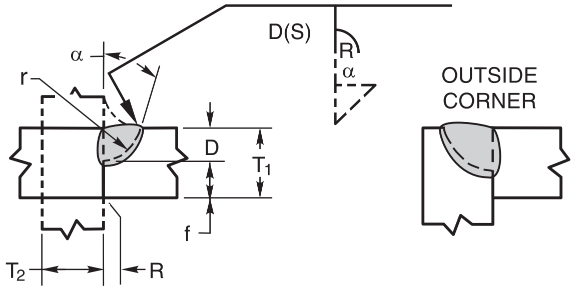
Figure 4.5 (Continued)—Details of Welded Joints for PJP Groove Welds (see 4.13.1) (Dimensions in Inches)

See Notes on Page 27

Single-J-groove weld (8)
T-joint (T)
Corner joint (C)

FOR CORNER AND T-JOINT RESTRICTIONS, SEE 4.11

FOR BUTT JOINT RESTRICTIONS, SEE 4.14



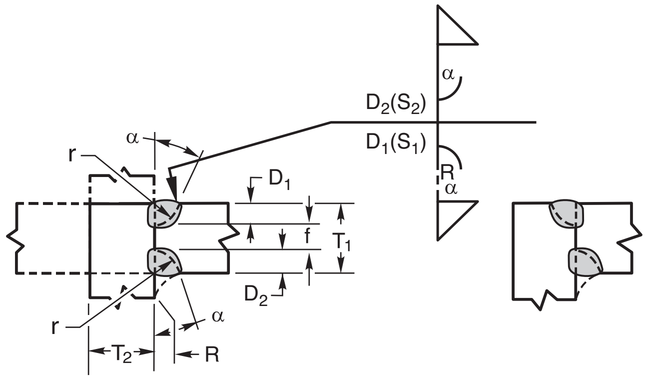
Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Weld Size (S)	Notes
				Root Opening Root Face Groove Radius Groove Angle	Tolerances				
		T_1	T_2		As Detailed (see 4.13.1)	As Fit-Up (see 5.3.4)			
SMAW	TC-P8	1/4 min.	U	R = 0 f = 1/8 min. r = 3/8 α = 45°	+1/16, –0 Not limited +1/4, –0 +10°, –0°	+1/8, –1/16 ±1/16 ±1/16 +10°, –5°	All	D	a, d, j
SMAW	C-P8*	1/4 min.	U	R = 0 f = 1/8 min. r = 3/8 α = 30°	+1/16, –0 Not limited +1/4, –0 +10°, –0°	+1/8, –1/16 ±1/16 ±1/16 +10°, –5°	All	D	a, d, j
GMAW FCAW	TC-P8-GF	1/4 min.	U	R = 0 f = 1/8 min. r = 3/8 α = 45°	+1/16, –0 Not limited +1/4, –0 +10°, –0°	+1/8, –1/16 ±1/16 ±1/16 +10°, –5°	All	D	d, j
GMAW FCAW	C-P8-GF*	1/4 min.	U	R = 0 f = 1/8 min. r = 3/8 α = 30°	+1/16, –0 Not limited +1/4, –0 +10°, –0°	+1/8, –1/16 ±1/16 ±1/16 +10°, –5°	All	D	d, j
SAW	TC-P8-S	7/16 min.	U	R = 0 f = 1/4 min. r = 1/2 α = 45°	±0 Not limited +1/4, –0 +10°, –0°	+1/16, –0‡ ±1/16 ±1/16 +10°, –5°	F	D	d, j
SAW	C-P8-S*	7/16 min.	U	R = 0 f = 1/4 min. r = 1/2 α = 30°	±0 Not limited +1/4, –0 +10°, –0°	+1/16, –0‡ ±1/16 ±1/16 +10°, –5°	F	D	d, j

‡Fit-up tolerance, see 5.3.2, for rolled shapes R may be 5/16 in in thick plates if backing is provided.
*Applies to outside corner joints.

Figure 4.5 (Continued)—Details of Welded Joints for PJP Groove Welds (see 4.13.1) (Dimensions in Inches)

See Notes on Page 27

Double-J-groove weld (9)
T-joint (T)
Corner joint (C)



FOR CORNER AND T-JOINT RESTRICTIONS, SEE 4.11

FOR BUTT JOINT RESTRICTIONS, SEE 4.14

Welding Process	Joint Designation	Base Metal Thickness (U = unlimited) T_1	T_2	Groove Preparation: Root Opening Root Face Groove Radius Groove Angle	Tolerances: As Detailed (see 4.13.1)	Tolerances: As Fit-Up (see 5.3.4)	Allowed Welding Positions	Total Weld Size ($S_1 + S_2$)	Notes
SMAW	TC-P9	1/2 min.	U	R = 0 f = 1/8 min. r = 3/8 α = 45°	+1/16, –0 –0 +1/4, –0 +10°, –0°	+1/8, –1/16 ±1/16 ±1/16 +10°, –5°	All	$D_1 + D_2$	a, d, g, j
GMAW FCAW	TC-P9-GF*	1/2 min.	U	R = 0 f = 1/8 min. r = 3/8 α = 30°	+1/16, –0 Not limited +1/4, –0 +10°, –0°	+1/8, –1/16 ±1/16 ±1/16 +10°, –5°	All	$D_1 + D_2$	d, g, j
SAW	C-P9-S	3/4 min.	U	R = 0 f = 1/4 min. r = 1/2 α = 45°	±0 Not limited +1/4, –0 +10°, –0°	+1/16, –0 ±1/16 ±1/16 +10°, –5°	F	$D_1 + D_2$	d, g, j
SAW	C-P9-S*	3/4 min.	U	R = 0 f = 1/4 min. r = 1/2 α = 20°	±0 Not limited +1/4, –0 +10°, –0°	+1/16, –0‡ ±1/16 ±1/16 +10°, –5°	F	$D_1 + D_2$	d, g, j
SAW	T-P9-S	3/4 min.	U	R = 0 f = 1/4 min. r = 1/2 α = 45°	±0 Not limited +1/4, –0 +10°, –0°	+1/16, –0‡ ±1/16 ±1/16 +10°, –5°	F	$D_1 + D_2$	d, g, j

‡Fit-up tolerance, see 5.3.2, for rolled shapes R may be 5/16 in in thick plates if backing is provided.
*Applies to outside corner joints.

Figure 4.5 (Continued)—Details of Welded Joints for PJP Groove Welds (see 4.13.1) (Dimensions in Inches)

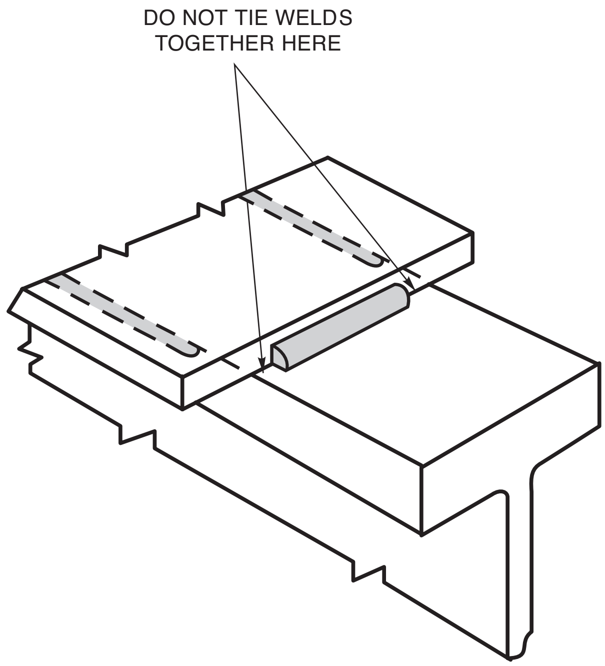
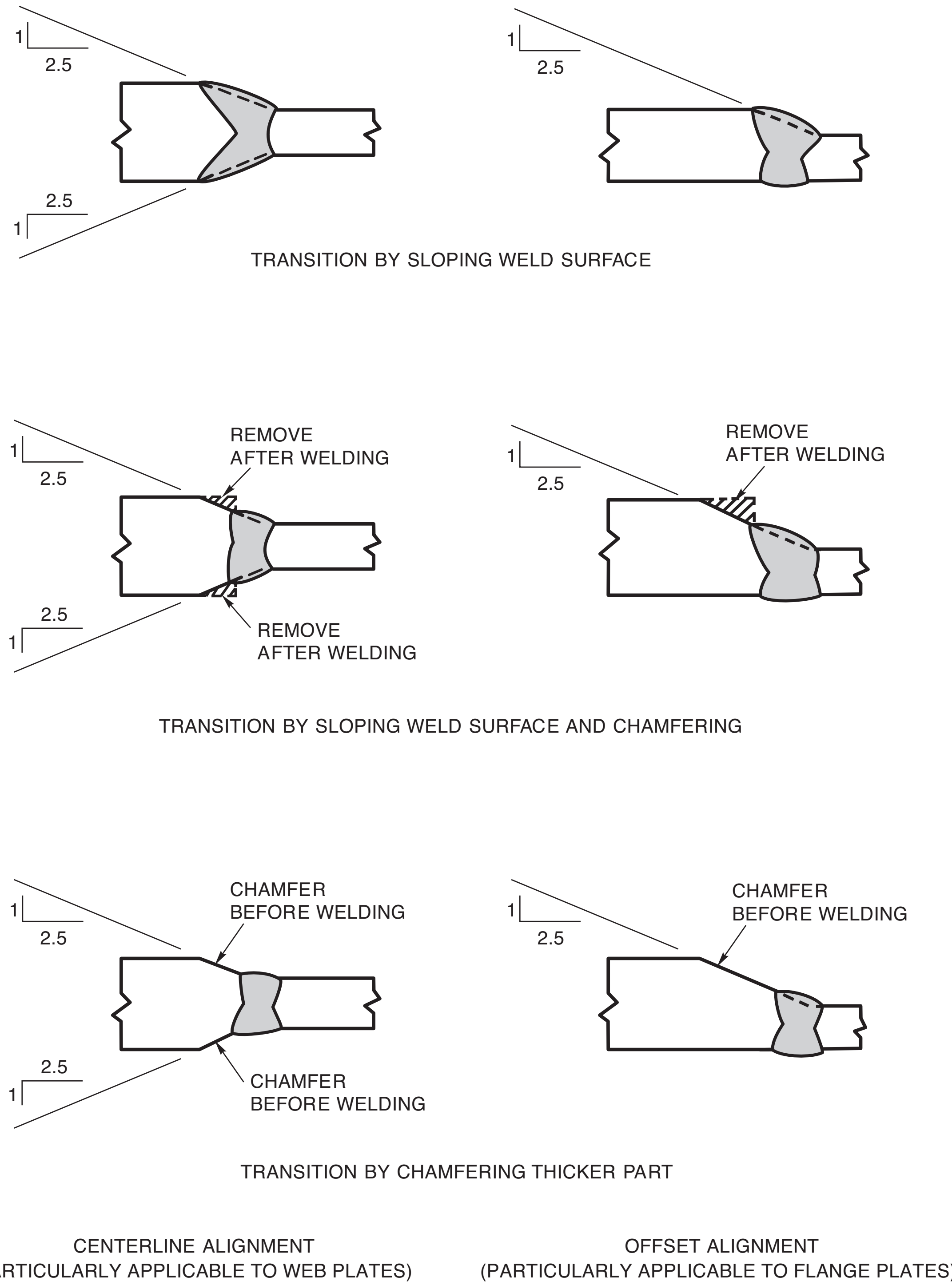


Figure 4.6—Fillet Welds on Opposite Sides of a Common Plane of Contact (see 4.8.8)



Notes:
1. Groove may be of any allowed or qualified type and detail.
2. Transition slopes shown are the maximum allowed.

Figure 4.7—Transition of Thickness at Butt Joints of Parts Having Unequal Thickness (see 4.17.5.1)

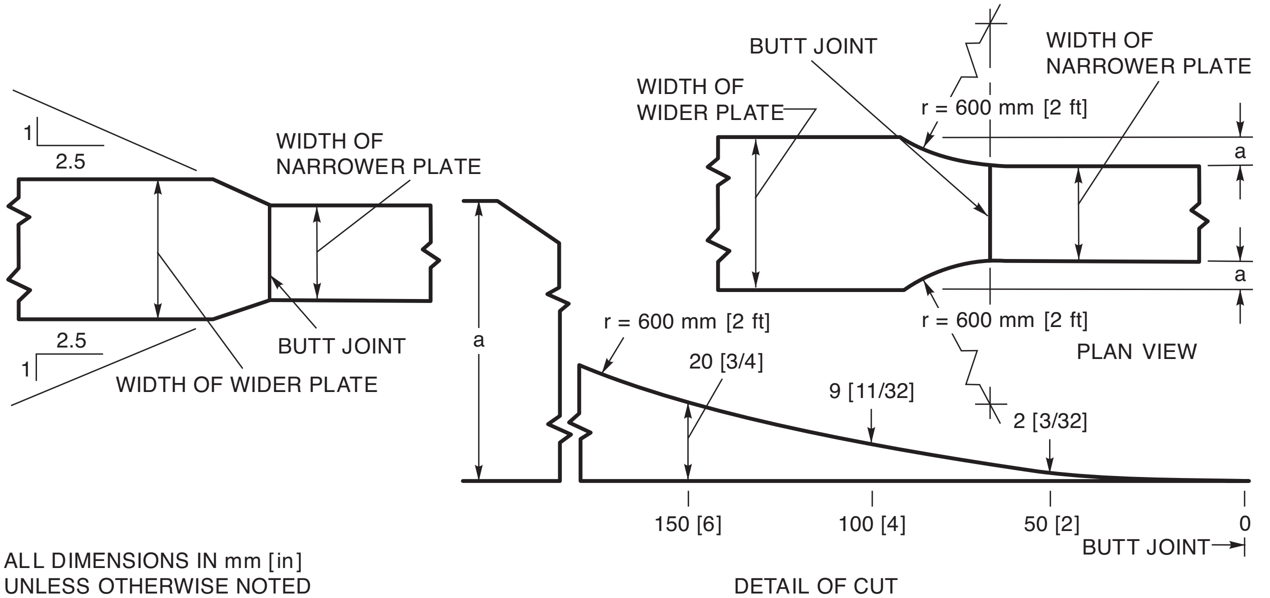


Figure 4.8—Transition of Width at Butt Joints of Parts Having Unequal Width (see 4.17.5.3)

5. Workmanship

5.1 General Requirements

5.1.1 All applicable paragraphs of this clause shall be observed in the fabrication of welded bridges under this code.

5.1.2 All welding and thermal-cutting equipment shall be so designed and manufactured, and shall be in such condition, as to enable designated personnel to follow the procedures and attain the results described elsewhere in the code.

5.1.3 Welding shall not be done when the ambient temperature is lower than –20°C [0°F] (see 6.2), when surfaces are wet or exposed to rain, snow, or high wind velocities, nor when welders are exposed to inclement conditions.

5.1.4 Size and lengths of welds shall be no less than those specified by design requirements and detailed drawings except as allowed by 8.26.1.7. The location of welds shall not be changed without approval.

5.1.5 Welds shall be prohibited on the work except as follows:

(1) Base-metal repair performed in conformance with ASTM A6/A6M, *Specification for General Requirements for Rolled Steel Plates, Shapes, Sheet Piling, and Bars*, Article 9, by the mill or fabricator

(2) All welds detailed on approved shop drawings

(3) Repair welds authorized by this code

(4) Other welds approved by the Engineer

5.2 Preparation of Base Metal

5.2.1 General. Base metal shall be sufficiently clean to permit welds to be made that will meet the weld quality requirements of this code.

5.2.2 Mill-Induced Surface Defects. Welds shall not be placed on surfaces that contain fins, tears, cracks, slag, or other base metal defects as defined in the base metal specifications.

5.2.3 Scale and Rust. Loose scale, thick scale, and thick rust shall be removed from the surfaces to be welded within 25 mm [1 in] of the weld. Welds may be made on surfaces that contain thin mill scale and rust if:

(1) the mill scale and rust can withstand vigorous hand wire brushing; and

(2) if the applicable weld quality requirements of this code can be met.

All mill scale shall be removed from the following:

(1) web-to-flange connections

(2) joint boundaries of groove welds subject to calculated tensile stress

5.2.4 Foreign Materials.

5.2.4.1 Surfaces to be welded, and surfaces adjacent to the weld, shall be cleaned to remove evident quantities of the following:

- Water
- Oil

- Grease
- Other hydrocarbon based materials

Welding on surfaces containing residual amounts of foreign materials is permitted providing the weld quality requirements of this code can be met.

5.2.4.2 Welds are permitted to be made on surfaces with anti-spatter compounds or protective coatings applied providing the weld quality requirements of this code can be met. Protective coatings are not permitted on web-to-flange connections or joints subject to calculated tensile stress.

5.2.5 In all thermal cutting, the cutting flame shall be so adjusted and manipulated as to avoid cutting beyond (inside) the prescribed lines. Steel and weld metal may be thermally cut, provided a smooth and regular surface free from cracks and notches is secured and provided that an accurate profile is secured by the use of a mechanical guide. Freehand thermal cutting shall be done only where approved by the Engineer.

For material up to 100 mm [4 in] thick, the maximum cut surface roughness value, as defined by ANSI B46.1, *Surface Texture*, shall be 25 µm [1000 µin], except where no calculated stress is present, the ends of members shall have a maximum surface roughness value of 50 µm [2000 µin]. For material over 100 mm [4 in] through 200 mm [8 in] thick, the maximum cut surface roughness value shall be 50 µm [2000 µin].

The following conditions may be fared by machining or grinding, provided that the actual net cross-sectional area that will remain after fairing is 98% or greater of the material's nominal area:

- Roughness exceeding the values of this section
- Occasional notches or gouges no more than 5 mm [3/16 in] deep on surfaces that are otherwise satisfactory and on material edges not to be welded

Fairing to the material surface shall have a slope not steeper than one in ten, with final machining or grinding striations parallel to the primary direction of stress. Cut surfaces and edges shall be left free of slag.

5.2.5.1 For steels other than M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W] steel, occasional notches or gouges in thermal-cut surfaces, resulting from improper operation of the cutting process may, with the approval of the Engineer, be repaired by welding. Material discontinuities exposed by thermal cutting, such as significant nonmetallic inclusions, shall not be repaired by welding unless RT or UT have defined the limits of the defects and the Engineer has approved the methods of defect removal and repair.

Approved repairs shall be made by (1) suitably preparing the discontinuity for welding, (2) welding using an approved low-hydrogen WPS, (3) observing all applicable requirements of this code, and (4) grinding the completed weld smooth and flush with the adjacent surface (see 5.6.2.1). Repair welds in members subject to tension or reversal of stress shall be inspected as described in 5.2.5.3.

5.2.5.2 For M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W] steel, defects in thermal cut surfaces shall not be repaired by welding except with the approval of the Engineer for occasional gouges and notches as follows:

(1) Notches or gouges not more than 5 mm [3/16 in] deep in plate edges that will form the faces of a groove welded joint and that will be subsequently completely fused with the weld may be repaired by welding. Nonmetallic stringers or pipe opening to those edges shall be removed to a depth of 6 mm [1/4 in] below the surface by grinding or chipping, followed by grinding, and the gouge shall be repaired by welding. Laminations opening to these edges shall be repaired in conformance with 5.2.6.

(2) Notches or gouges not more than 5 mm [3/16 in] deep in material edges that will form a fillet welded corner joint may be repaired by welding only on the part of the edge that will become the faying surface for the joint and the fusion zone of the fillet weld. The part of the defect outside the toe of the completed fillet weld shall be removed in conformance with 5.2.6.

(3) Repair shall be made by suitably preparing the defective area, then welding in conformance with following an approved WPS and the applicable requirements of Clause 6. The completed weld shall be finished smooth and flush (see 5.6.2.2) with the adjacent surface.

5.2.5.3 Welded repairs to the surfaces and edges of tension and reversal-of-stress members shall be subject to UT and MT. Weld quality shall conform to the requirements of 8.26.

5.2.6 Visual Inspection and Repair of Base Metal Cut Edges

5.2.6.1 The following provisions shall apply to allowable repairs to discontinuities discovered either (1) by visual inspection of base-metal cut edges before fabrication or welding, or (2) during routine examination of welded joints by RT or UT, in all steels covered by these specifications, in thicknesses up to and including 100 mm [4 in] maximum.

These discontinuities principally result from gas pockets or blow holes and shrinkage cavities that are manifested as "laminations" or "pipe" characterized by a distinct separation of metal parallel to the plane of the base metal. To a lesser extent, these discontinuities result from entrapped slag, refractory, or deoxidation products manifested as deposits of foreign material in the steel, parallel to the plane of the base metal. Multiple discontinuities located in the same plane shall be considered continuous when they are separated by a distance less than 5% of the base metal thickness or the length of the smaller of two adjacent discontinuities.

5.2.6.2 The limits of acceptability and the repair of visually observed edge discontinuities shall be in conformance with Table 5.1, in which the length of discontinuity is the visible long dimension on the cut edge of the base metal and the depth is the distance that the discontinuity extends into the base metal from the cut edge. Base-metal edges may be at any angle with respect to the direction of rolling, but the direction of discontinuities shall be considered with respect to the direction of the base-metal edges. The limits of all internal discontinuities required to be explored, which are not explored to their full depth by other means, shall be determined by UT.

5.2.6.3 In making any repairs, the amount of metal removed shall be the minimum necessary to remove the discontinuity or determine that the allowable limit shall not be exceeded. Gouging of the discontinuity may be done from either the base-metal surface or edge. All repairs of discontinuities by welding shall conform to the applicable provisions of this code and an approved WPS.

5.2.6.4 The corrective procedures described in Table 5.1 shall not apply to discontinuities in rolled base-metal surfaces. Such discontinuities may be corrected by the fabricator in conformance with the provisions of ASTM A6/A6M.

5.2.6.5 Edges of base metal shall be inspected, and required repairs shall be completed as feasibly early in the fabrication sequence so as to allow maximum opportunity for the fabricator to incorporate repaired plates in the least critical areas.

5.2.6.6 Discontinuities in a base-metal edge such as Type Y in Figure 5.1 shall be removed by machining or grinding if the actual net cross-sectional area that would remain after removal of the discontinuity is 98% or greater of the area of the base metal based on nominal dimensions. Such removals shall be faired to the base metal edge with a slope not exceeding one in ten. Machining or grinding marks perpendicular to the applied stress shall not exceed a surface roughness of 3 μm [125 μin]. Welding repairs shall be prohibited for Type Y discontinuities in M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W] steel. In steels other than M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W] steel, a Type Y discontinuity may be repaired by welding with the approval of the Engineer.

5.2.6.7 For discontinuities over 25 mm [1 in] in length with depth found to be greater than 25 mm [1 in], discovered before welding by visual inspection of cut edges of base metal, or found in welded joints during examination by RT or UT, the following procedures should be observed:

(1) Where discontinuities such as W, X, or Y in Figure 5.1 are observed prior to completing the joint, the size and shape of the discontinuity shall be determined by UT. The area of the discontinuity shall be determined as the area of total loss of back reflection, when tested in conformance with the procedure of ASTM A435/A435M, *Specification for Straight Beam Ultrasonic Examination of Steel Plates*.

(2) For acceptance of Type W, X, and Y discontinuities, the area of the discontinuity (or the aggregate area of multiple discontinuities) shall not exceed 4% of the plate area (plate length times plate width) with the following exception: If the length of the discontinuity, or the aggregate width of discontinuities on any transverse section, as measured perpendicular to the base-metal length, exceeds 20% of the base-metal width, the 4% restriction of base-metal area shall be reduced by the percentage amount of the width exceeding 20%. (For example, if a discontinuity is 30% of the base-metal width, the area of discontinuity cannot exceed 3.6% of the base-metal area.)

The discontinuity on the cut edge of the base metal shall be gouged out to a depth of 25 mm [1 in] below its intersection with the surface by chipping, air carbon arc gouging, or grinding to form a groove cross section with a minimum groove radius (r) of 6 mm [1/4 in] and a minimum groove angle (α) of 20 degrees, and shall be blocked off by SMAW, FCAW-G, or GMAW in at least four weld layers not exceeding 3 mm [1/8 in] in thickness per layer. The repair may be completed by SAW (except for active fluxes), SMAW, FCAW-G, or GMAW with normal restrictions on layer thickness and welding processes.

(3) If a discontinuity Z, not exceeding the allowable area in 5.2.6.7(2), is discovered after the joint has been completed and is determined to be 25 mm [1 in] or more away from the face of the weld, as measured on the base-metal surface, no repair of the discontinuity is required by this code. If the discontinuity Z is less than 25 mm [1 in] away from the face of the weld, it shall be removed to a distance of 25 mm [1 in] from the fusion zone of the weld by chipping, air carbon arc gouging, or grinding to form a groove cross section with a minimum groove radius (r) of 6 mm [1/4 in] and a minimum groove angle (α) of 20 degrees. It shall then be blocked off by welding with SMAW, FCAW-G, or GMAW for at least four layers not exceeding 3 mm [1/8 in] in thickness per layer. SAW (except for active fluxes), SMAW, FCAW-G, or GMAW may be used for the remaining layers with normal restrictions on layer thickness and welding processes.

(4) If the area of the discontinuity W, X, Y, or Z exceeds the allowable in 5.2.6.7(2), the base metal or subcomponent shall be rejected and replaced, or repaired at the discretion of the Engineer.

(5) The aggregate length of weld repair shall not exceed 20% of the length of the base-metal edge without approval of the Engineer.

(6) For discontinuities of Types W and X, all repair welds in M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W] steel shall be made with low-hydrogen electrodes not exceeding 4.0 mm [5/32 in] in diameter. All repair welds in M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W] steel shall be inspected not less than 48 hours after they are completed, and the groove weld shall not be made until after the repair weld has been approved by the Engineer.

(7) All repair welding shall conform to the requirements of an approved WPS.

5.2.7 Reentrant corners of base-metal cut edges shall be formed to provide a smooth transition with a radius of not less than 25 mm [1 in] that meets the adjacent edges without offset or cutting past the point of tangency. The reentrant corners may be formed by various methods, including thermal cutting, drilling or gouging, followed by finishing to meet the surface requirements of 5.2.5.

5.2.8 Radii of beam copes and weld access holes shall provide a smooth transition, free of notches or cutting past the points of tangency between adjacent surfaces.

5.2.9 Joint and edge preparation and removal of unacceptable weld or base metal may be done by machining, thermal cutting, plasma or air carbon arc cutting and gouging, grinding, or chipping, followed by grinding to remove residue and satisfy the WPS-specified joint geometry.

Oxygen cutting shall not be used for partial removal of welds when slag or other materials may deflect the oxygen stream and damage the remaining metal. Where carbon arc gouging or cutting is used, carbon and copper residue and dross shall be removed from the areas to be welded. Air carbon arc gouged surfaces shall be finished to bright metal.

5.2.10 Edges of built-up beam and girder webs shall be cut to the prescribed camber with suitable allowance for shrinkage due to cutting and welding. However, members with camber exceeding the tolerances of 5.5.3 may be corrected by heating as described in 5.4.8. Excess camber may be corrected by heating without the Engineer's approval.

5.2.11 Corrections of errors in camber of quenched and tempered steel shall be given prior approval by the Engineer.

5.2.12 Edges of material thicker than specified in the following list shall be trimmed if and as required to produce a satisfactory welding edge wherever a weld along the edge is to carry calculated stress:

Sheared edges of material thicker than	12 mm [1/2 in]
Rolled edges of plates thicker than	10 mm [3/8 in]
Toes of angles or rolled shapes thicker than	16 mm [5/8 in]
Universal mill plates or edges of flanges of wide flange sections thicker than	25 mm [1 in]

The form of edge preparation for butt joints shall conform to the requirements of 4.12 except as modified by 4.7.

5.3 Assembly

5.3.1 The parts to be joined by fillet welds shall be brought into as close contact as practicable. The root opening shall not exceed 5 mm [3/16 in] except in cases involving either shapes or plates 75 mm [3 in] or greater in thickness if, after straightening and in assembly, the root opening cannot be closed sufficiently to meet this tolerance. In such cases, a maximum root opening of 8 mm [5/16 in] may be used, with a backing weld or suitable backing. If the root opening is greater than 2 mm [1/16 in], the leg of the fillet weld shall be increased by the amount of the root opening or the Contractor shall demonstrate that the required weld size has been obtained.

5.3.1.1 The separation between faying surfaces of plug and slot welds, and of butt joints landing on a backing, shall not exceed 2 mm [1/16 in].

5.3.1.2 The use of filler plates shall be prohibited except as specified on the drawings or as specially approved by the Engineer and made in conformance with 4.5.

5.3.2 The root opening between parts to be joined by PJP groove welds parallel to the member length (bearing joints excepted) shall be zero, or as small as practicable.

5.3.2.1 The root opening between parts shall not exceed 5 mm [3/16 in] except in cases involving rolled shapes or plates 75 mm [3 in] or greater in thickness if, after straightening and in assembly, the root opening cannot be closed sufficiently to meet this tolerance. In such cases, a maximum root opening of 8 mm [5/16 in] may be used with a backing weld or suitable backing and the final weld meets the requirements for weld size.

5.3.2.2 Tolerances for bearing joints shall be in conformance with the applicable contract specifications.

5.3.3 Parts to be joined by complete penetration groove welds in butt joints shall be aligned so the full section of the thinner element is effectively fused, and the offset from the shop drawing configuration does not exceed 10% of the thickness of the thinner part joined or 3 mm [1/8 in], whichever is less. Measurement of offset shall be based on either the centerline of elements or the surfaces to be co-planar, as defined on the drawings. For elements deflected to meet these limits, the average slope created shall not exceed 1:25.

5.3.4 With the exclusion of ESW and EGW, and with the exception of 5.3.4.1 for root openings in excess of those allowed below and illustrated in Figure 5.2, the dimensions of the cross section of the groove welded joints which vary from those shown on the detail drawings by more than the tolerances shown in Figure 5.2 shall require approval by the Engineer for correction.

Allowable Root Openings		
	Root Not Gouged, mm [in]	Root Gouged, mm [in]
(1) Root face of joint	± 2 [±1/16]	Not limited
(2) Root opening of joints without steel backing	± 2 [±1/16]	± 2 [±1/16] –3 [–1/8]
Root opening of joints with steel backing	+6 [+ 1/4] –2 [–1/16]	Not applicable
(3) Groove angle of joint	+ 10° – 5°	+ 10° – 5°

5.3.4.1 Root openings wider than those allowed in 5.3.4, but not greater than twice the thickness of the thinner part or 20 mm [3/4 in], whichever is less, may be corrected by welding to acceptable dimensions prior to joining the parts by welding.

5.3.4.2 Root openings larger than those allowed in 5.3.4.1 may be corrected by welding only with the approval of the Engineer.

5.3.5 Groove preparations produced by gouging shall be substantially in conformance with groove profile dimensions as described in Figures 4.4 and 4.5.

5.3.6 Members to be welded shall be brought into correct alignment and held in position by bolts, clamps, wedges, guy lines, struts, and other suitable devices, or by tack welds until welding has been completed. The use of jigs and fixtures is recommended where practicable. Suitable allowances shall be made for warpage and shrinkage (see 5.4.4, 5.4.5, 5.4.6, and 5.4.7.)

5.3.7 Tack Welds

5.3.7.1 tack welds shall be subject to the same requirements as the final welds, except as exempted in 5.3.7.3. Tack welding shall be performed in accordance with a WPS meeting the requirements of Clause 5 unless exempted by 5.3.7.3. Tack welds shall be cleaned and visually inspected before subsequent welding.

5.3.7.2 Multipass Tack Welds. Multipass tack welds shall have cascaded ends.

5.3.7.3 Remelted Tack Welds. Tack welds made in accordance with 5.3.7.3(1) and 5.3.7.3(2) shall be considered fully remelted and incorporated into the final weld and shall be exempt from the following requirements:

(a) Minimum preheat requirements shall not apply.

(b) WPSs for tack welding shall not require qualification testing in accordance with Clause 7.

(1) **Exemption Requirements.** The following conditions shall be met for the exemptions of 5.3.7.3 to apply:

(a) The tack welds shall be made in a single pass.

(b) The filler metal for tack welding is listed in Table 6.1.

(c) No other welding process may be used to weld over a FCAW-S tack weld unless qualified by 7.7.7.1.

(2) **Remelting Conditions.** To ensure that tack welds are fully remelted, the following shall apply:

(a) The remelting capability of the subsequent welding process and procedure is verified by macroetch in accordance with 7.18.2 and 7.19.2.

(b) The maximum tack weld size used in production shall not exceed the tack weld size used in the qualification testing.

(c) The heat input of the pass used to remelt the tack in production shall not be less than that used in the qualification testing.

5.3.7.4 Unincorporated Tack Welds.

(1) Removal. Tack welds not incorporated into the final weld shall be removed in such a manner that the base metal is not damaged. Base metal damaged during tack weld removal may be repaired when approved by the Engineer. If the repair involves welding, it shall be done in conformance with 5.7.1.

(2) Cracked Base Metal. The removal of tack welds may expose cracked base metal. When cracked base metal is discovered after tack welds are removed, all other tack weld removal locations in the tension regions on the member shall be tested by magnetic particle testing (MT) to assure that no cracks are present. If the MT testing reveals cracks, hardness testing of the HAZ shall be required. Hardness values shall not exceed Rockwell C30 in the HAZ. These excessively hard HAZs shall be removed by shallow grinding.

5.3.7.5 Broken Tack Welds.

(1) General. If a tack weld breaks before welding of the joint has begun, the broken tack weld shall be removed, and if necessary, replaced.

(2) Exemptions. Tack welds that meet the requirements of 5.3.7.3 need not be repaired if the tack breaks after welding on that particular joint has begun.

5.3.7.6 Tack Welding of Backing.

(1) Tack Welding within the Joint. Tack welding of steel backing shall, where practicable, be done within the joint so that all tack welds will be incorporated into the final weld.

(2) Tack Welding Outside of the Joint. Tack welds used to attach steel backing and placed external to the weld joint shall be made continuous by fillet welding for the full length of the backing, or shall be removed by grinding, at the Contractor's option.

5.3.8 Temporary Welds. Temporary welds shall be subject to the same WPS requirements as final welds. They shall be removed unless otherwise allowed by the Engineer. When they are removed, the surface shall be made flush with the original surface. There shall be no temporary welds in tension zones of members of quenched and tempered steels. Temporary welds at other locations shall be shown on shop drawings. Removal of temporary welds shall conform to the requirements of 5.3.7.4.

5.3.9 Joint Root Openings. Joint root openings may vary as described in 4.12 and 4.13. However, for automatic or mechanized welding using FCAW, GMAW, or SAW, the maximum root opening variation (minimum to maximum opening as fit-up) may not exceed 3 mm [1/8 in]. Variations greater than 3 mm [1/8 in] shall be locally corrected prior to automatic or mechanized welding.

5.3.10 Assembly Sequence. J- and U-grooves may be prepared before or after assembly. Second-side grooves may be prepared by air carbon arc gouging and grinding after welding the first side. Before welding, the J- or U-groove shall conform to the provisions of this subclause.

5.3.11 Joint Detail Dimensional Tolerances. Dimensions of groove welds specified on design or detailed drawings may vary from the dimensions shown in Figure 4.4 or Figure 4.5 within the limits described in 5.3.4. J- and U-grooves may be prepared before or after assembly.

5.4 Control of Distortion and Shrinkage

5.4.1 In assembling and joining parts of a structure or of built-up members and in welding reinforcing parts to members, the procedure and sequence shall minimize distortion and shrinkage.

5.4.2 Insofar as practicable, all welds shall be made in a sequence that will balance the applied heat of welding while the welding progresses.

5.4.3 The Contractor shall prepare a welding sequence for a member or structure that, in conjunction with the WPSs and overall fabrication methods, will produce members or structures meeting the quality requirements specified. The welding sequence and distortion control program shall be submitted to the Engineer, for information and comment, before the start of welding on a member or structure in which shrinkage or distortion is likely to affect the adequacy of the member or structure. The distortion control program shall include standard mechanical or heat straightening procedures to be utilized when common distortion control practice must be supplemented to achieve specified tolerances.

5.4.4 The direction of the general progression in welding on a member shall be from points where the parts are relatively fixed in position with respect to each other toward points where they have a greater relative freedom of movement.

5.4.5 Joints expected to have significant shrinkage should usually be welded before joints expected to have lesser shrinkage. They should also be welded with as little restraint as possible.

5.4.6 All shop splices in each component part of a cover-plated beam or built-up member shall be made before the component part is welded to other component parts of the member. Long members or member sections may be made by shop or field splicing subsections, each made in conformance with this subclause (see 4.17.6).

5.4.7 In making welds under conditions of severe external shrinkage restraint, the welding shall be carried continuously to completion or to a point that will ensure freedom from cracking before the joint is allowed to cool below the minimum specified preheat and interpass temperature.

5.4.8 To achieve or restore the required geometry, elements may be aligned by:

(1) applied force causing yielding ("mechanical bending")

(2) methods that use controlled heating with restraint or support (including "heat shrink" or upset shortening)

(3) With Engineer approval, by a combination of controlled heating and mechanical means.

5.4.8.1. Elements to be heated shall be supported to minimize stress from gravity and external forces that would interfere with the desired results.

5.4.8.2 For any application of heat, the maximum temperature of the heated areas shall not exceed 600°C [1100°F] for M 270M/M 270 (A709/A709M) Grades HPS 485W [HPS 70W] and HPS 690W [HPS 100W] steels, or 650°C [1200°F] for the other steels listed in Table 6.1.

5.4.8.3 Accelerated cooling shall not be applied to steel above 315°C [600°F].

5.4.8.4 When mechanical means are used in combination with heat, the force shall not be initially applied or increased when steel temperature is either below 5°C [40°F] or between 150°C [300°F] and 370°C [700°F].

5.4.8.5 Mechanical forces shall be released before welding the element to other members.

5.5 Dimensional Tolerances

5.5.1 Allowable variations in straightness of built-up axial members, such as columns and primary truss members, regardless of cross section, shall not exceed:

Lengths of less than 10 m [30 ft]	1 mm/m [1/8 in/10 ft] total length, m [ft]
Lengths of 10 m to 15 m [30 ft to 45 ft]	10 mm [3/8 in]
Lengths over 15 m [45 ft]	10 mm + 1 mm/m × [length (m) – 15 m] 3/8 in + 1/8 in/10 ft × [length (ft) – 45 ft]

5.5.2 Allowable variations in straightness of built-up flexural members, such as beams or girders, regardless of cross section, where there is no specified camber or sweep, shall not exceed:

1 mm/m [1/8 in/10 ft] total length, m [ft]

5.5.3 For rolled beams or built-up girders, with the top flange not embedded in concrete or with the top flange embedded in concrete with a designed haunch, regardless of cross section, the allowable variation from specified camber at shop assembly (for drilling holes for field splices or preparing field welded splices) shall be:

at midspan –	0, +40 mm [1-1/2 in] for spans < 30 m [100 ft] –0, + 20 mm [3/4 in] for spans < 30 m [100 ft]
at supports,	0 for end supports ±3 mm [1/8 in] for interior supports
at intermediate points, where: *a = distance in meters [ft] from the inspection point to the nearest support* *S = span length in meters [ft]* *b = 40 mm [1-1/2 in] for spans ≥30 m [100 ft]* *b = 20 mm [3/4 in] for spans < 30 m [100 ft]*	$-0 + \frac{4\,(a)b\,(1-a/s)}{s}$

See Table 5.2 for tabulated values.

For members whose top flange is embedded in concrete without a designed concrete haunch, the allowable variation from required camber at shop assembly (for drilling holes for field splices or preparing field welded splices) shall be:

at midspan,	±20 mm [3/4 in] for spans ≥ 30 m [100 ft] ±10 mm [3/8 in] for spans < 30 m [100 ft]
at supports,	0 for end supports ±3 mm [1/8 in] for interior supports

at intermediate points,	$\pm \frac{4\,(a)b\,(1-a/s)}{s}$
where: *a = distance in meters [ft] from the inspection point to the nearest support* *S = span length in meters [ft]* *b = 20 mm [3/4 in] for spans ≥ 30 m [100 ft]* *b = 10 mm [3/4 in] for spans < 30 m [100 ft]*	

See Table 5.3 for tabulated values.

Regardless of how the camber is shown on the detail drawings, the sign convention for the allowable variation is plus (+) above, and minus (–) below, the detailed camber shape.

These provisions shall also apply to an individual member when no field splices or shop assembly is required.

Camber measurements shall be made in the no-load condition.

5.5.4 Allowable variation in specified sweep for horizontally curved rolled beams or built-up girders shall be 1 mm/m [1/8 in/10 ft] of total length, m [ft], provided the member has sufficient lateral flexibility to allow the attachment of diaphragms, cross-frames, lateral bracing, etc., without damaging the structural member or its attachments.

5.5.5 Allowable lateral variation between the actual and theoretical web centerline at the flange surface shall not exceed 6 mm [1/4 in].

5.5.6 For allowable variations from flatness of web for built-up girders, see (1) through (4) below:

(1) For a given location, the least panel dimension, d, is the lesser of either the web depth between flanges or the longitudinal spacing between transverse components (stiffeners, connection plates). A girder web's variation from flatness is the maximum offset of the web face from its theoretical location within a given panel. The "theoretical web face" is based on its location at panel boundaries (flanges, stiffeners). A reference line parallel to the theoretical web face may be used for measuring offsets.

A girder web's variation from flatness shall be evaluated by comparing its actual and theoretical locations. Offsets shall be measured from the actual web face to the theoretical web face location.

(2) Variation from flatness of webs having a depth, D, and a thickness, t, in panels bounded by stiffeners or flanges, or both, whose least panel dimension is d shall not exceed the following (all dimensions in mm [in]):

Intermediate stiffeners on both sides of web:
Interior girders
where D/t < 150—maximum variation = d/115
where D/t ≥150—maximum variation = d/92
Fascia girders
where D/t < 150—maximum variation = d/130
where D/t ≥ 150—maximum variation = d/105
Intermediate stiffeners on one side only of web:
Interior girders
where D/t < 100— maximum variation = d/100
where D/t ≥ 100— maximum variation = d/67
Fascia girders
where D/t < 100—maximum variation = d/120
where D/t ≥ 100—maximum variation = d/80
No intermediate stiffeners
maximum variation = D/150

See Annex C for illustration of terms and tabulation.

(3) Web distortion of twice the allowable tolerances of 5.5.6(2) shall be satisfactory when occurring at the end of a girder that has been drilled, or subpunched and reamed either during assembly or to a template for a field bolted splice, provided, when the splice plates are bolted, the web assumes the proper dimensional tolerances.

(4) If architectural considerations require tolerances more restrictive than described above, specific reference shall be included in the bid documents.

5.5.7 Combined warpage and tilt of flange at any cross section of built-up I- or H-shaped members shall be determined by measuring the offset at the toe of the flange from a line normal to the plane of the web through the intersection of the centerline of the web with the outside surface of the flange plate. This offset shall not exceed 1/100 of the total width of the flange or 6 mm [1/4 in], whichever is greater, at any point along the member, except that at any bearing this offset shall not exceed that described in 5.5.9 and that abutting parts to be joined by groove welds in butt joints shall conform to 5.3.3.

Warpage and tilt of rolled section flanges shall not exceed limits specified in ASTM A6/A6M (AASHTO M160M/M160), except that at bearings they shall not exceed limits described in 5.5.9 and that abutting parts to be joined by groove welds in butt joints shall conform to 5.3.3.

For top flanges of open-section box girders, combined warpage and tilt of flange shall be determined by measuring the offset at the toe of the flange from a line through the intersection of the centerline of the web with the outside surface of the flange plate, at the designed angle of the flange to the web. The offset shall not exceed 1/50 of the distance from the web centerline to the nearest edge of the flange or 6 mm [1/4 in], whichever is greater. (See Figure 5.3.)

5.5.8 The maximum allowable variation from specified depth for built-up members, measured at the web centerline, shall not exceed:

For depths up to 1 m [36 in] inclusive	±3 mm [1/8 in]
For depths over 1 m to 2 m [36 in to 72 in] inclusive	±5 mm [3/16 in]
For depths over 2 m [72 in]	+ 8 mm [5/16 in] –5 mm [3/16 in]

5.5.9 The bearing ends of bearing stiffeners shall be flush and square with the web and shall have at least 75% of this area in contact with the flanges.

When bearing against a steel base or seat, all steel components shall fit within 1 mm [1/32 in] for 75% of the projected area of the web and stiffeners. Rolled beams or built-up girders without stiffeners shall bear on the projected area of the web on the outer flange surface within 1 mm [1/32 in] and the included angle between web and flange shall not exceed 90° in the bearing length.

5.5.10 Where tight fit of intermediate stiffeners is specified, it shall be defined as allowing a gap of up to 2 mm [1/16 in] between stiffener and flange.

5.5.11 The out-of-straightness variation of intermediate stiffeners shall not exceed 12 mm [1/2 in] with due regard to any members that frame into them.

5.5.12 The out-of-straightness variation of bearing stiffeners shall not exceed 6 mm [1/4 in] up to 2 m [6 ft]. The actual centerline of the stiffener shall lie within the thickness of the stiffener as measured from the theoretical centerline location.

5.5.13 Other dimensional tolerances not covered by 5.5 shall be individually determined and mutually agreed upon by the Contractor and the Engineer with proper regard for erection requirements.

5.5.14 At mechanically connected joints and splices of main members, when faying surfaces on either side of a connection are to be on a common plane, the offset shall be no greater than 2 mm [1/16 in] after fill plates, if any, are added.

5.5.15 The corresponding surfaces of secondary member parts, at mechanically fastened connections, shall show no offset greater than 3 mm [1/8 in].

5.5.16 Ends of members which are to be field connected by welding shall be shop assembled or assembled to a template to ensure conformance to 5.3.1, 5.3.2, 5.3.3, and 5.3.4.

5.6 Weld Profiles

5.6.1 Fillet Welds. The faces of fillet welds may be slightly convex, flat, or slightly concave as shown in Figure 5.4(A) and (B) with none of the unacceptable profiles shown in Figure 5.4(C). The convexity C of a weld or individual surface bead shall not exceed 0.07 times the actual face width of the weld or individual bead, respectively, plus 1.5 mm [0.06 in] [see Figure 5.4(B)]. These profile requirements shall not apply to the ends of intermittent fillet welds outside the specified effective length or for outside corner joints; these exceptions do not modify the weld quality provisions, including the undercut limits of 8.26.

5.6.2 Groove Welds. In the case of butt and outside corner joints, the face reinforcement shall not exceed 3 mm [1/8 in] in height and shall have gradual transition to the plane of the base metal surface; see Figure 5.4(D). Welds shall be free of unacceptable groove weld profiles shown in Figure 5.4(E).

5.6.2.1 Removal of Weld Reinforcement. When surfaces of butt joints are specified in contract documents to be finished flush, the following shall apply:

(1) The nominal thickness of the thinner base metal or weld metal shall not be reduced by more than:

Base Metal Thickness (t)	Maximum Thickness Reduction
$t \le 20$ mm	1 mm
20 mm $< t \le 60$ mm	5% t
$t > 60$	2 mm
Base Metal Thickness (t)	Maximum Thickness Reduction
$t \le 5/8$ in	1/32 in
5/8 in $< t \le 2\text{-}1/2$ in	5% t
$t > 2\text{-}1/2$ in	1/8 in

(2) The weld or thinner base metal cross-sectional area along the weld length shall not be reduced to less than 98% of the nominal cross section.

(3) Remaining reinforcement shall not exceed 1 mm [1/32 in] and shall blend smoothly into the base metal surfaces except no reinforcement is allowed on faying surfaces.

(4) After finishing, surfaces shall be free from undercut. Undercut removal shall be such that the base metal and weld metal blend smoothly without exceeding the limits of (1) and (2) above.

(5) If chipping is used for reinforcement removal, it shall be followed by finishing.

All reinforcement shall be removed where the weld forms a part of the faying surface.

5.6.2.2 Surface Finish. Where surface finishing is required, surface roughness values shall not exceed 6 μm [250 μin]. Surfaces finished to values over 3 μm [125 μin] through 6 μm [250 μin] shall be finished parallel to the direction of primary stress. Surfaces finished to values of 3 μm [125 μin] or less may be finished in any direction, subject to the following additional requirements: butt joints between parts subject to tensile stress, whether joining parts of equal or unequal width or thicknesses, shall be finished flush, or to a smooth transition, to a roughness not exceeding 3 μm [125 μin].

5.6.3 Overlap. Welds shall be free from overlap.

5.7 Repairs

5.7.1 The removal of weld metal or portions of the base metal may be done by machining, air carbon arc cutting and gouging, thermal cutting, chipping, or grinding. It shall be done in such a manner that the remaining weld metal or base metal is not nicked or undercut (see 5.2.9 for restrictions on the use of air carbon arc gouging and thermal cutting).

Unacceptable portions of the weld shall be removed without substantial removal of the base metal. Any additional weld metal shall be deposited using a qualified WPS. The surface shall be thoroughly cleaned before welding.

5.7.2 The Contractor has the option of either repairing an unacceptable weld, or removing and replacing the entire weld or the entire assembly, except as modified by 5.7.4. The repaired or replaced weld shall be reinspected by the method originally used, and the same technique and quality acceptance criteria shall be applied. If the Contractor elects to repair the weld, it shall be corrected as follows:

5.7.2.1 Overlap or Excessive Convexity. Excess weld metal shall be removed.

5.7.2.2 Excessive Concavity of Weld or Crater, Undersize Welds, Undercutting. Surfaces shall be prepared (see 5.11) and additional weld metal deposited.

5.7.2.3 Excessive Weld Porosity, Excessive Slag Inclusions, Incomplete Fusion. Unacceptable portions shall be removed (see 5.7.1) and rewelded.

5.7.2.4 Cracks in Weld or Base Metal. The extent of the crack shall be ascertained by use of MT, liquid penetrant testing (PT), or other equally positive means; the metal shall be removed for the full length of the crack plus 50 mm [2 in] beyond each end of the crack, and rewelded.

5.7.3 Members damaged or distorted beyond provisions of the distortion control plan shall be corrected as described in 5.4.8.

5.7.4 Prior approval of the Engineer shall be obtained for repairs to base metal (other than those required by 5.2), repair of major or delayed cracks, repairs to ESW and EGW welds with internal defects, or for a revised design to compensate for deficiencies.

5.7.5 The Engineer shall be notified before improperly fitted and welded members are cut apart.

5.7.6 If, after an unacceptable weld has been made, work is performed rendering that weld inaccessible, or has created new conditions that make correction of the unacceptable weld dangerous or ineffectual, then the original conditions shall be restored by removing welds or members, or both, before the corrections are made. If this is not done, the deficiency shall be compensated for by additional work performed according to an approved revised design.

5.7.7 Welded Restoration of Material with Mislocated Holes. Except where restoration by welding is necessary for structural or other reasons, punched or drilled mislocated holes may be left open or may be filled with a bolt. When base metal with mislocated holes is restored by welding, the following requirements apply:

5.7.7.1 Base metal not subjected to dynamic tensile stress may be restored by welding, provided the Contractor prepares and follows a repair WPS. The repair weld soundness shall be verified by ultrasonic testing (UT) or radiographic testing (RT) as approved by the Engineer.

5.7.7.2 Base metal subject to dynamic tensile stress may be restored by welding providing the following apply:

(1) The Engineer approves both repair by welding and the repair WPS.

(2) The repair WPS is followed in the work and the soundness of the restored base metal is verified by UT or RT, as specified in the contract documents for examination of tension groove welds or as approved by the Engineer.

5.7.7.3 In addition to the requirements of 5.7.7.1 and 5.7.7.2, when holes in quenched and tempered steels are restored by welding, the following shall apply:

(1) Appropriate filler metal, heat input, and postweld heat treatment (when PWHT is required) shall be used.

(2) Sample welds shall be made using the repair WPS.

(3) RT of the sample welds shall verify that weld soundness conforms to the requirements of 8.26.2.1.

(4) One reduced section tension test (weld metal), two side-bend tests (weld metal); and three CVN tests of the HAZ (coarse grained area) removed from sample welds shall be used to demonstrate that the mechanical properties of the repaired area conform to the specified requirements of the base metal.

5.7.7.4 Weld surfaces shall be finished as specified in 5.6.2.2.

5.8 Peening

5.8.1 When approved by the Engineer, peening may be used to prevent cracking and lamellar tears by mechanically reducing residual stresses created by welding. To prevent sharp impressions, peening shall be performed by mechanically striking convex surfaces of intermediate weld beads or layers with a round tool with a 6 mm [1/4 in] radius (unless otherwise approved). Root and final passes shall not be peened. When approved by the Engineer, final passes that contain excess weld metal may be peened, provided all of the excess weld metal and all peening marks are removed by finishing.

Peening shall be done when the weld is at a temperature of 65°C–260°C [150°F–500°F]. Care shall be taken to avoid striking fusion boundaries or the base metal. Peening energy shall be sufficient to mechanically elongate the surface of the weld without creating overlapping or cracking. Pneumatic tools shall be operated in a manner that prevents contamination of the weld by moisture, oil, or other materials.

5.8.2 Manual slag hammers, chisels, and lightweight vibrating tools for the removal of slag and spatter may be used and shall not be considered peening.

5.9 Caulking

Caulking of welds shall be prohibited.

5.10 Arc Strikes

Care shall be taken to avoid arc strikes outside the area of permanent welds on any base metal. Cracks or blemishes caused by arc strikes shall be ground to remove all of the defect. On tension and reversal of stress members, MT (preferably the yoke method) shall be used to determine that no cracks are present in the structure (see 8.7.8.2). Hardness tests shall be employed as stated in 5.3.7.4.

5.11 Weld Cleaning

5.11.1 In-Process Cleaning. Before welding over previously deposited metal, all slag shall be removed and the weld and adjacent base metal shall be brushed clean. This requirement shall apply not only to successive layers but also to successive beads and to the crater area when welding is resumed after any interruption. It shall not, however, restrict the welding of plug and slot welds in conformance with 6.23 and 6.24.

5.11.2 Cleaning of Completed Welds. Slag shall be removed from all completed welds and the weld and adjacent base metal shall be cleaned by brushing or other suitable means. Tightly adherent spatter remaining after the cleaning operation shall be acceptable unless its removal shall be required for the purpose of NDT or painting. Welded joints shall not be painted until after welding has been completed and the weld has been accepted.

5.12 Weld Termination

5.12.1 Welds shall be terminated at the end of a joint in a manner that will ensure sound welds. Whenever possible, this shall be done by use of weld tabs (extension bars and run-off plates) placed in a manner that will duplicate the joint detail being welded.

5.12.2 Weld Tabs and Sumps. Weld tabs and sumps used in welding shall conform to the following requirements:

(1) The weld tab and sumps may be of any of the steels described in 1.2.2 except that M 270M/M 270 Grade HPS 690W [HPS 100W] (A709/A709M Grade HPS 100W [HPS 690W]) tabs and sumps shall not be used on lower strength steels.

(2) Base metal used as temporary weld extensions shall be exempt from toughness testing.

5.12.3 Weld tabs (extension bars and run-off plates) and sumps shall be removed upon completion and cooling of the weld, and the ends of the welds shall be made smooth and flush with the edges of the abutting parts.

5.12.4 Ends of welded butt joints required to be flush shall be finished so as not to reduce the width beyond the detailed width or the actual width furnished, whichever is greater, by more than 3 mm [1/8 in] or so as not to leave reinforcement at each end that exceeds 3 mm [1/8 in]. Ends of welded butt joints shall be faired to adjacent plate or rolled shape edges at a slope not to exceed 1 in 10 unless otherwise shown on the drawings.

5.13 Weld Backing

5.13.1 Backing. Steel backing shall conform to the following requirements:

(1) When welding any approved steel described in 1.2.2, backing may be of any of the steels described in 1.2.2 except M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W] backing shall not be used on lower strength steels.

(2) When welding a steel qualified in conformance with 7.4.2, backing may be Grade HPS 485W [HPS 70W], 345 [50], 345S [50S], 345W [50W], HPS 345W [HPS 50W], 250 [36], or the steel qualified.

(3) Backing not exceeding 10 mm × 30 mm [3/8 in × 1-1/4 in], furnished as bar stock or cut from plate, shall be exempt from CVN testing requirements.

5.13.2 Groove welds made with the use of steel backing shall have the weld metal thoroughly fused with the backing. Steel backing shall be continuous for the full length of each weld made with backing. A continuous length of backing may be made by welding shorter sections together under the following conditions:

(1) All welds shall be CJP groove welds made with the same controls as similar CJP groove welds in the structure.

(2) RT or UT shall be used to assure weld soundness.

(3) All welding and testing of the backing shall be complete before the backing is used to make the structural weld.

5.13.3 Steel backing on welds transverse to the direction of computed stress shall be removed, and the joint shall be finished smooth. Steel backing parallel to the direction of stress or not subject to computed stress need not be removed.

5.13.3.1 For welds in compression in T-joints and columns, steel backing need not be removed.

5.13.3.2 Where the steel backing of longitudinal welds is externally attached to the base metal by welding, such welding shall be continuous for the length of the backing.

5.13.4 The recommended minimum nominal thickness of backing, provided that the backing shall be of sufficient thickness to prevent melting through, is shown in the following table:

Process	Minimum Nominal Thickness, mm [in]
SMAW	5 [3/16]
GMAW	6 [1/4]
FCAW-S	6 [1/4]
FCAW-G	10 [3/8]
SAW	10 [3/8]

5.13.5 Steel backing shall be placed and held in intimate contact with the base metal. The maximum gap between steel backing and the base metal at the weld root shall be 2 mm [1/16 in], as shown in Figure 5.2(A).

5.13.6 Groove and fillet welds may be backed by copper, flux, glass tape, iron powder, or similar materials to provide an appropriate back-bead shape or to prevent melting through. Roots of welds may also be sealed by means of root passes deposited with SMAW low-hydrogen electrodes or by other approved arc WPSs.

Copper shall not be used as a backing when there is any possibility that the welding arc may strike the copper.

Welds made against backing other than base metal or approved low-hydrogen weld metal shall be subject to WPS qualification testing under the provisions of 7.7.5 and approval by the Engineer. In SAW, flux that fills gaps not exceeding 5 mm [3/16 in] between adjacent parts shall not be considered to be backing and shall not require WPS qualification testing.

Table 5.1
Limits on Acceptability and Repair of Cut Edge Discontinuities of Material (see 5.2.6.2)

Description of Discontinuity	Plate Repair Required
Any discontinuity 25 mm [1 in] in length or less	None, need not be explored
Any discontinuity over 25 mm [1 in] in length and 3 mm [1/8 in] maximum depth	None, but the depth should be explored[a]
Any discontinuity over 25 mm [1 in] in length with depth over 3 mm [1/8 in] but not greater than 6 mm [1/4 in]	Remove, need not weld
Any discontinuity over 25 mm [1 in] in length with depth over 6 mm [1/4 in] but not greater than 25 mm [1 in]	Completely remove and weld Aggregate length of welding shall not exceed 20% of the length of the material edge being repaired
Any discontinuity over 25 mm [1 in] in length with depth greater than 25 mm [1 in]	See 5.2.6.7

[a] A spot check of 10% of the discontinuities on the oxygen-cut surface in question should be explored by grinding to determine depth. If the depth of any one of the discontinuities explored exceeds 3 mm [1/8 in], then all of the discontinuities remaining on that edge shall be explored to determine depth. If none of the discontinuities explored on the 10% spot check have a depth exceeding 3 mm [1/8 in], then the remainder of the discontinuities on that edge need not be explored.

Table 5.2
Camber Tolerance for Typical Girder (see 5.5.3)

Camber Tolerance, mm [in]

Span \ a/S	0.1	0.2	0.3	0.4	0.5
≥30 m [100 ft]	14 [9/16]	25 [1]	34 [1-1/4]	38 [1-7/16]	40 [1-1/2]
<30 m [100 ft]	7 [1/4]	13 [1/2]	17 [5/8]	19 [3/4]	20 [3/4]

Table 5.3
Camber Tolerance for Girders without a Designed Concrete Haunch (see 5.5.3)

Camber Tolerance, mm [in]

Span \ a/S	0.1	0.2	0.3	0.4	0.5
≥30 m [100 ft]	7 [1/4]	13 [1/2]	17 [5/8]	19 [3/4]	20 [3/4]
<30 m [100 ft]	4 [1/8]	6 [1/4]	8 [5/16]	10 [3/8]	10 [3/8]

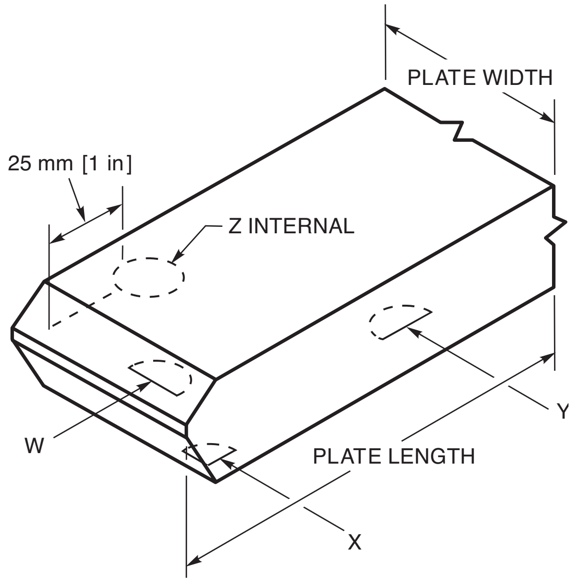
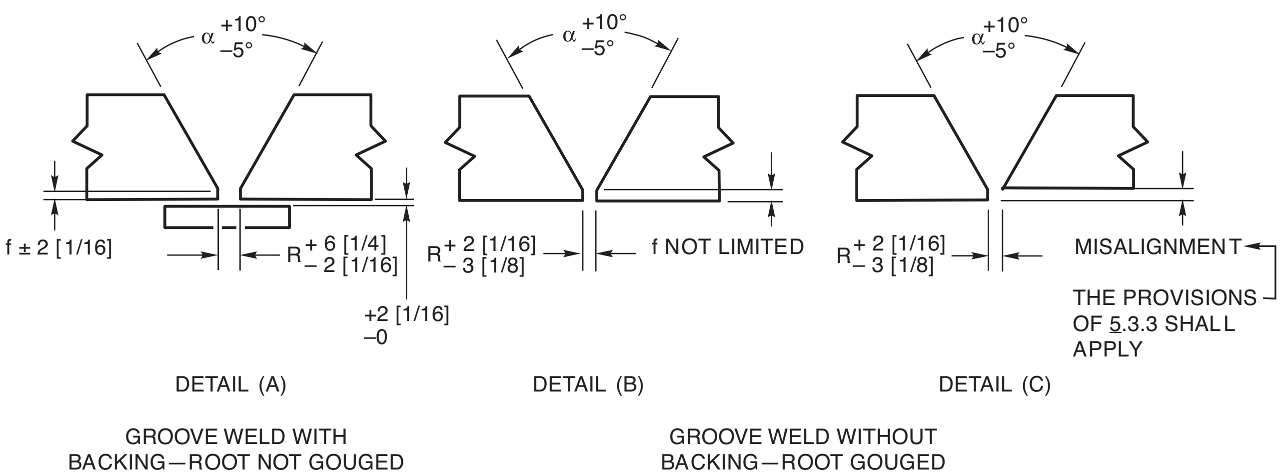


Figure 5.1—Discontinuities in Cut Plate (see 5.2.6.6)



Notes:
1. α = groove angle.
2. R = root opening.
3. f = foot face.
4. The groove configurations shown are for illustration only.
5. All dimensions in mm [in].

Figure 5.2—Workmanship Tolerances in Assembly of Groove Welded Joints (see 5.3.4)

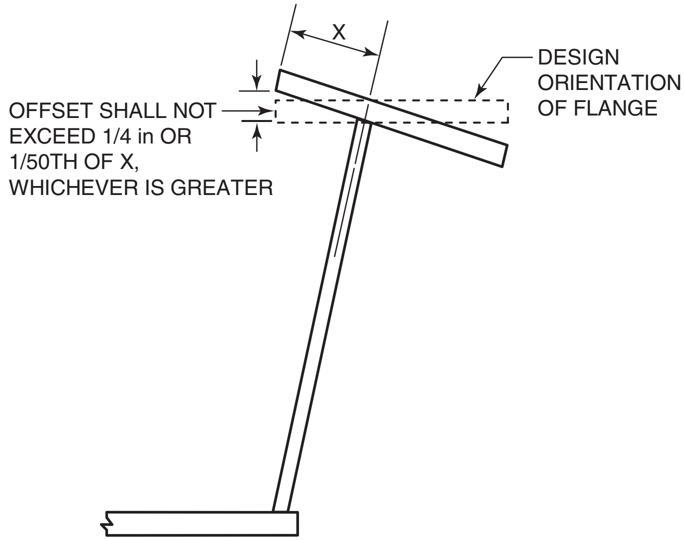
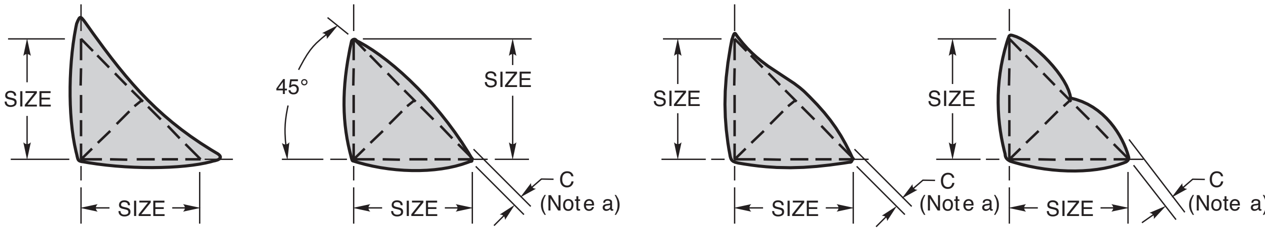


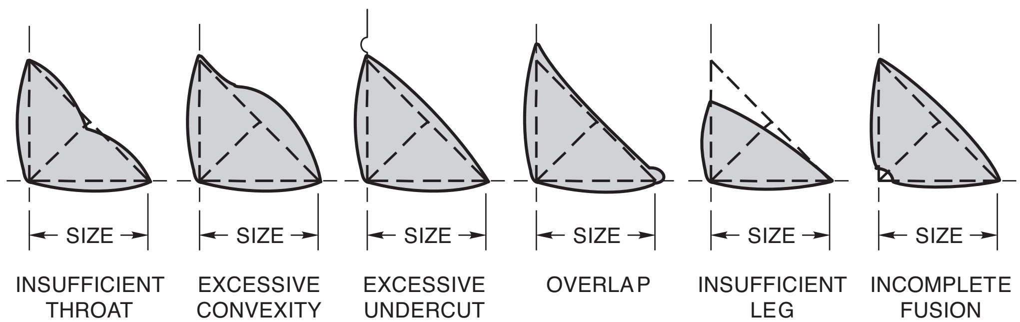
Figure 5.3—Flange Offset for Box Girders



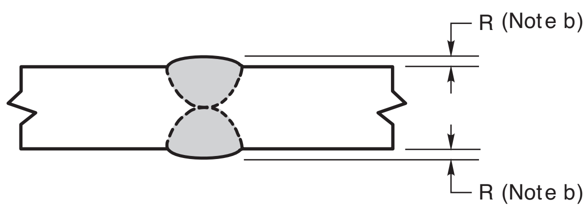
(A) DESIRABLE FILLET WELD PROFILES

(B) ACCEPTABLE FILLET WELD PROFILES

[a]Convexity, C, of a weld or individual surface bead shall not exceed 0.07 times the actual face width of the weld or individual bead, respectively, plus 1.5 mm [0.06 in].

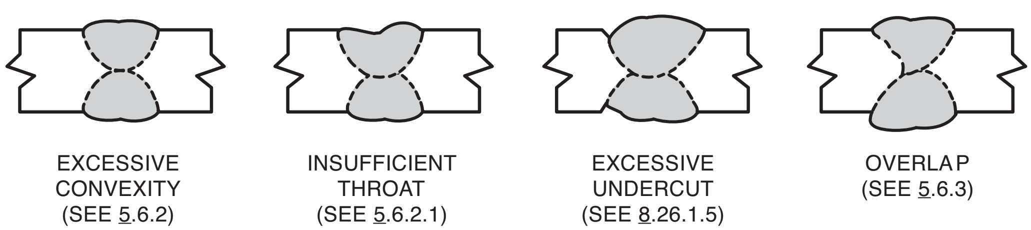


(C) UNACCEPTABLE FILLET WELD PROFILES



(D) ACCEPTABLE GROOVE WELD PROFILE

[b]Reinforcement R shall not exceed 3 mm [1/8 in] (see 5.6.2).



(E) UNACCEPTABLE GROOVE WELD PROFILES IN BUTT JOINTS

Figure 5.4—Acceptable and Unacceptable Weld Profiles (see 5.6)

6. Technique

Part A
General Requirements

6.1 Filler Metal Requirements

6.1.1 Matching Filler Metal. For matching weld metal, the electrode or electrode/flux combination shall be selected from Table 6.1 for the base metal to be used in the work. WPSs for joints involving two base metals of different specified yield strengths shall use filler metal matching the lower strength base metal.

When undermatching filler metal is required or allowed by the contract documents, the electrode or electrode-flux combination shall be of the strength class shown on the shop drawings, and the filler metal shall be selected from Table 6.1, consistent with design requirements.

6.1.2 Mechanical Properties. The mechanical properties of filler metals used to produce fillet and groove welds are described in Table 7.3.

6.1.2.1 For weld joints containing M 270M/M 270 (A 709/A 709M) Grade HPS 485W [HPS 70W] materials, the maximum filler metal diffusible hydrogen content shall conform to the diffusible hydrogen requirements of the AWS filler metal specifications optional supplemental designator H8. GMAW with solid electrodes shall be considered to meet this requirement.

6.1.3 Consumable Requirements. Welding consumables used in production shall meet the requirements of either 6.1.3.1 or 6.1.3.2, at the Contractor's option. Filler metals and fluxes used for WPS qualification testing shall be exempt from the requirements of 6.1.3.1 or 6.1.3.2, provided the WPS and qualification test reports show the same manufacturer's brand and type of filler metal and flux was used.

6.1.3.1 Consumable Manufacturer Quality Assurance Program. Under this option, welding consumables shall be produced under continuing quality assurance programs audited and approved by one or more of the following agencies:

(1) American Bureau of Shipping (ABS)

(2) Lloyd's Register of Shipping

(3) American Society of Mechanical Engineers (ASME)

6.1.3.2 Heat or Lot Testing. Under this option, welding consumables shall be heat or lot tested by the manufacturer to determine conformance with the applicable AWS A5.XX specification (or Annex H in the case of ESW). Certified copies of test results shall be provided to the Engineer. Heat and lot shall be as defined in AWS A5.01M/A5.01 (ISO 14344 MOD), *Welding Consumables—Procurement of Filler Metals and Fluxes*. Consumables shall be tested by welding as specified in the appropriate AWS specification. All tests required by AWS A5.01, Schedule J, shall be performed and reported.

Materials of the same specification, classification, brand, product trade name, and manufacturer (but not necessarily the same heat or lot) to be combined during production welding shall be used for heat and lot testing.

6.1.4 Consumable Certifications

6.1.4.1 The Contractor shall furnish manufacturer's AWS A5.XX certificates of conformance for all electrodes, electrode and flux combinations, and electrode and shielding gas combinations used in production.

6.1.4.2 Certificates shall include results of all tests required by the applicable AWS A5.XX specification (Annex H for ESW).

6.1.4.3 AWS A5.XX certificate of conformance tests shall be made using consumables of the same specification, classification, and product trade name and brand, and welded with the same shielding gas (for gas shielded processes) that will be used in production.

6.1.4.4 For sizes of SMAW electrodes for which tests are not required by AWS A5.1/A5.1M, *Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding*, or AWS A5.5/A5.5M, *Specification for Low-Alloy Steel Electrodes for Shielded Metal Arc Welding*, the test reports for electrodes of the size nearest to the size used shall be furnished.

6.1.4.5 For SAW and ESW, tests shall be welded using flux with the same manufacturer, brand, and trade name as will be used in production.

6.1.4.6 For consumables supplied in accordance with 6.1.3.1, the test shall have been made within one year prior to manufacture of the consumables furnished. Consumables supplied in accordance with 6.1.3.2 shall not have any time limits.

6.1.4.7 The certificate of conformance shall include the manufacturer's certification that the process and material requirements were the same for manufacturing the tested and furnished electrodes or electrode/flux combinations. The certificate shall contain all pertinent information concerning the tests required by the filler metal specification. An example certification form is shown in Annex N, Form N-1.

6.1.4.8 In lieu of requiring a Contractor to furnish copies of manufacturer's certificates of conformance for each shipment of consumables on a project, the contracting authority may maintain a list of approved brands of consumables for which satisfactory certificates of conformance made within one year have been previously submitted. If this alternative is elected, the list shall be available to project Engineers and Contractors.

6.1.5 After filler metal has been removed from its original package, it shall be protected or stored so that its characteristics and welding properties are not affected (see 6.5.2).

6.1.6 For exposed, bare, unpainted applications of M 270M/M 270 (A709/A709M) Grades 345W [50W] and HPS 345W [HPS 50W] steels requiring weld metal with atmospheric corrosion resistance and coloring characteristics similar to that of the base metal, the electrode or electrode-flux combination shall be in conformance with Table 6.2. In multiple-pass welds, the weld metal may be deposited so that at least two layers on all exposed surfaces and edges are deposited with one of the filler metals listed in Table 6.2, provided the underlying layers are deposited with one of the filler metals described in Table 6.1.

6.1.7 For single-pass welding, other than ESW or EGW, of exposed, bare, unpainted applications of M 270M/ M 270 (A709/A709M) Grades 345W [50W] and HPS 345W [HPS 50W] steels requiring weld metal with atmospheric corrosion resistance and coloring characteristics similar to that of the base metal, the following variations from Table 6.2 may be made. This shall also apply to unpainted applications of HPS 485W [HPS 70W] when undermatching is allowed.

6.1.7.1 Shielded Metal Arc Welding (SMAW). Single-pass fillet welds up to 6 mm [1/4 in] maximum and 6 mm [1/4 in] groove welds made with a single pass or a single pass each side may be made using an E70XX low-hydrogen electrode.

6.1.7.2 Submerged Arc Welding (SAW). Single-pass fillet welds up to 8 mm [5/16 in] maximum and groove welds made with a single pass or single pass each side may be made with an electrode-flux combination listed in Table 6.1.

6.1.7.3 Gas Metal Arc Welding (GMAW). Single-pass fillet welds up to 8 mm [5/16 in] maximum and groove welds made with a single pass or a single pass each side may be made using an ER70S-X or E70C-XM electrode listed in Table 6.1.

6.1.7.4 Flux Cored Arc Welding (FCAW). Single-pass fillet welds up to 8 mm [5/16 in] maximum and groove welds made with a single pass or single pass each side, may be made using an E7XT-X electrode listed in Table 6.1.

6.1.8 For ESW or EGW welding of exposed, bare, unpainted applications of M 270M/M 270 (A709/A709M) Grades 345W [50W] and HPS 345W [HPS 50W] steels requiring weld metal with atmospheric corrosion resistance and coloring characteristics similar to that of the base metal, the electrode or electrode-flux combination shall produce weld metal that conforms to the requirements described in Table 6.2. The chemical composition of the weld metal deposited on a standard filler metal test pad, where there is minimal dilution of the base metal, shall conform to one of the chemical compositions provided in the list of electrodes described in Table 6.2. The chemical composition of deposited ESW or EGW weld metal will not exactly match either the electrode or the base metal, since there is considerable base-metal dilution. The electrode or electrode/flux combination shall be approved by the Engineer.

6.2 Preheat and Interpass Temperature Requirements

The preheat and interpass temperature shall be sufficient to prevent cracking. Experience has shown that the minimum temperatures specified in Table 6.3 are adequate to prevent cracking in most cases. However, increased preheat temperatures may be necessary in situations involving higher restraint, higher hydrogen, lower welding heat input, or steel composition at the upper limits of the specification. Conversely, lower preheat temperatures may be adequate to prevent cracking, depending on restraint, hydrogen level, and actual steel composition or higher welding heat input.

6.2.1 Minimum Preheat and Interpass Temperature. The minimum preheat and interpass temperatures shall be as specified in Table 6.3, except that preheat is not required for tack welding conforming to 5.3.7.3, stud welding, ESW, and EGW.

6.2.1.1 Extent of Preheat. Preheat temperature shall be maintained during the welding operation for a distance at least equal to the thickness of the thickest welded part, but not less than 75 mm [3 in] in all directions from the edge of the weld joint, measured at the location of the welding arc.

6.2.1.2 Minimum preheat and interpass temperatures may be established on the basis of steel composition, thickness, and restraint using recognized methods of prediction such as those provided in Annex F.

However, should the use of such guidelines result in temperatures lower than required by 6.2.1, the minimum temperature shall be qualified by performing tests acceptable to the Engineer.

6.2.1.3 Optional reduced preheat and interpass temperatures for M 270M/M 270 Grade HPS 690W [HPS 100W] (A709/A709M Grade HPS 100W [HPS 690W]) may be used in accordance with the requirements of Annex G.

6.2.2 Maximum Preheat and Interpass Temperature. The maximum preheat and interpass temperature shall be as specified in the WPS. For M 270M/M 270 (A709/ A709M) Grade HPS 690W [HPS 100W], the maximum preheat and interpass temperature shall not exceed 205°C [400°F] for thicknesses up to 40 mm [1-1/2 in] inclusive, and 230°C [450°F] for greater thicknesses. For HPS 485W [HPS 70W], the maximum preheat and interpass temperature shall be 230°C [450°F] for all thicknesses.

6.2.2.1 Extent of Interpass. The maximum interpass temperature shall be measured at a distance of 25 mm to 75 mm [1 in to 3 in] in all directions from the edge of the weld, measured just prior to welding the next pass.

6.2.3 Base Metal/Thickness Combinations. Temperature controls shall be based upon the thickness and grades of the base metal. For combinations of base metals, preheat and interpass temperatures shall be based upon the higher of the required temperatures.

6.2.4 Special Conditions. Thick material, or highly restrained joints or repair welds, shall be preheated by the Contractor above the minimum specified temperatures as required to prevent cracking or minimize lamellar tearing.

6.2.5 Minimum Ambient Temperature. Welding shall not be done when the ambient temperature in the immediate vicinity of the weld is lower than –20°C [0°F]. The ambient environmental temperature may be lower than – 20°C [0°F], provided supplemental heat and protection from the elements are sufficient to maintain a temperature adjacent to the weldment at –20°C [0°F], or higher.

6.2.6 Measurement of Minimum Temperature. When the base metal is below the temperature listed for the welding process being used and the thickness of material being welded, it shall be preheated in such a manner that the steel on which weld metal is being deposited is at or above the specified minimum temperature for a distance equal to the thickness of the part being welded, but not less than 75 mm [3 in] in all directions from the point of welding. To increase the effectiveness of preheat without increasing the temperature, at the Contractor's option, the area and depth that is heated may be increased beyond the minimum specified. There shall be no limit to the maximum area that may be preheated unless stated in the contract documents.

6.2.7 Minimum Base Metal Temperature. When the base-metal temperature is below 0°C [32°F], the weld area shall be heated to at least 20°C [70°F], and this minimum temperature shall be maintained during welding.

6.2.8 Alternate SAW and Preheat Interpass Temperature. The minimum preheat and interpass temperature requirements for SAW made with parallel or multiple electrodes may be modified under the provisions of 6.10.4.

6.3 Heat Input Control for Grade HPS 690W [HPS 100W] Steel

When M 270M/M 270 Grade HPS 690W [HPS 100W] (A709/A709M Grade HPS 100W [HPS 690W]) steels are welded, welding heat input shall be appropriate for the thickness of steel to be joined and the preheat and interpass temperature used. Heat input shall not exceed the steel producer's recommendations. Table 12.8 may be used for guidance in welding M 270M/M 270 (A709/ A709M) Grade HPS 690W [HPS 100W] steel.

6.4 Stress Relief Heat Treatment

6.4.1 General. Where required by the contract drawings or specifications, welded assemblies shall be stress-relieved by heat treating. Finish machining shall preferably be done after stress relieving. Thermal stress relieving of weldments involving M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W] steel is prohibited unless required to maintain dimensional stability or avoid stress corrosion-induced cracking. If heat treatment is required for tension elements, the contract may require prototype testing with similar configurations to evaluate effects on HAZ grain growth, ductility, and toughness.

6.4.2 Requirements. The stress relief treatment shall conform to the following requirements:

6.4.2.1 Initial Furnace Temperature. The temperature of the furnace shall not exceed 315°C [600°F] at the time the welded assembly is placed in it.

6.4.2.2 Rate of Heating. Above 315°C [600°F] the rate of heating in °C/hr shall not exceed 5600 divided by the maximum metal thickness in mm [in °F/hr the rate of heating shall not exceed 400°F per hour divided by the maximum metal thickness in inches], but not more than 220°C/hr [400°F/hr]. The rates of heating and cooling need not be less than 55°C [100°F] per hour. During the heating period, variation in temperature throughout the portion of the part being heated shall be no greater than 140°C [250°F] within any 5 m [15 ft] interval of length.

6.4.2.3 Holding Time. After a maximum temperature of 600°C [1100°F] is reached on quenched and tempered steels, or a mean temperature range between 600°C [1100°F] and 650°C [1200°F] is reached on other steels, the temperature of the assembly shall be held within the specified limits for a time not less than specified in Table 6.4, based on weld thickness. When the specified stress relief is for dimensional stability, the holding time shall not be less than specified in Table 6.4, based on the thickness of the thicker part. During the holding period, the highest and lowest temperature throughout the portion of the assembly being heated shall not vary by greater than 85°C [150°F].

6.4.2.4 Rate of Cooling. Above 315°C [600°F], cooling shall occur in a closed furnace or cooling chamber at a rate in °C/hr not exceeding 7000 divided by the maximum metal thickness in mm [in °F/hr the cooling rate shall be no greater than 500°F per hour divided by the maximum metal thickness in inches], but not more than 280°C/hr [500°F/hr]. Below 315°C [600°F], the assembly may be cooled in still air.

6.4.3 Alternative PWHT. Alternatively, when it is impractical to postweld heat treat to the temperature limitations described in 6.4.2, welded assemblies may be stress-relieved at lower temperatures for longer periods of time, as given in Table 6.5.

Part B
Shielded Metal Arc Welding (SMAW)

6.5 Electrodes for SMAW

6.5.1 SMAW Electrodes. Electrodes for SMAW shall conform to the requirements of the latest edition of AWS A5.1/A5.1M, *Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding*, or to the requirements of AWS A5.5/A5.5M, *Specification for Low-Alloy Steel Electrodes for Shielded Metal Arc Welding*. All electrodes for SMAW shall be of the low-hydrogen classification.

6.5.2 Low-Hydrogen Drying Requirements. All electrodes having low-hydrogen coverings conforming to AWS A5.1/A5.1M shall be purchased in hermetically sealed containers or shall be dried in conformance with the manufacturer's written drying instructions. Electrodes having a low-hydrogen covering conforming to AWS A5.5/A5.5M shall be purchased in hermetically sealed containers or shall be dried at least one hour at temperatures between 370°C and 425°C [700°F and 800˚F] before being used. Electrodes shall be dried prior to use if the hermetically sealed container shows evidence of damage. Immediately after opening of the hermetically sealed container or removal of the electrodes from drying ovens, electrodes shall be stored in ovens held at a temperature of at least 120°C [250°F]. After the opening of hermetically sealed containers or removal from drying or storage ovens, electrode exposure to the atmosphere shall not exceed the requirements of 6.5.2.1.

6.5.2.1 Approved Atmospheric Exposure Periods. Electrodes exposed to the atmosphere upon removal from drying or holding ovens or hermetically sealed containers shall be used within the time limit shown in Table 6.6 or redried at 230°C to 290°C [450°F to 550°F] for two hours minimum, except as provided in 6.5.2.3.

6.5.2.2 Short Exposure Times. Electrodes exposed to the atmosphere for periods less than those allowed by Table 6.6 may be returned to a holding oven maintained at 120°C [250°F] minimum and after a minimum period of four hours at that temperature may be reissued.

6.5.2.3 Optional Supplemental Moisture-Resistant Designators. E70XX-X, E80XX-X, E90XX-X, E100XX-X, and E110XX-X electrodes with the AWS filler metal specifications optional supplemental moisture resistance designator "R" may be exposed to the atmosphere for up to nine hours when welding steels with a minimum specified yield strength of 345 MPa [50 ksi] or less. Moisture-resistant electrodes shall be received in containers that bear the additional designator "R" as part of the AWS classification.

6.5.3 Electrode Restrictions for Grade HPS 690W. When used for welding M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W] steel, electrodes shall be dried at least one hour at temperatures between 370°C and 425°C [700°F and 800°F] before being used, whether furnished in hermetically sealed containers or otherwise.

6.5.4 Redrying Electrodes. Electrodes that conform to the provisions of 6.5.2 shall be redried no more than one time. Electrodes that have been wet shall not be used.

6.6 Procedures for SMAW

6.6.1 Flat Position. The work shall be positioned for flat position welding whenever practical.

6.6.2 Suitability. The classification and size of electrode, arc length, voltage, and amperage shall be suited to the thickness of the material, type of groove, welding positions, and other circumstances attending the work. Welding current shall be within the range recommended by the electrode manufacturer.

6.6.3 Maximum Electrode Diameter. The maximum diameter of electrodes shall be as follows:

(1) 6.4 mm [1/4 in] for all welds made in the flat position, except root passes

(2) 6.4 mm [1/4 in] for horizontal fillet welds

(3) 6.4 mm [1/4 in] for root passes of fillet welds made in the flat position and groove welds made in the flat position with backing and with a root opening of 6 mm [1/4 in] or more

(4) 4.0 mm [5/32 in] for welds made in the vertical and overhead position

(5) 5.0 mm [3/16 in] for root passes of groove welds and for all other welds not included under 6.6.3(1), (2), (3), and (4)

6.6.4 Minimum Root Pass Size. The minimum size of a root pass shall be sufficient to prevent cracking.

6.6.5 Maximum Root Pass Thickness. The maximum thickness of root passes in groove welds shall be 6 mm [1/4 in].

6.6.6 Maximum Single-Pass Fillet Weld Size. The maximum size of single-pass fillet welds and root passes of multiple-pass fillet welds shall be as follows:

(1) 10 mm [3/8 in] in the flat position

(2) 8 mm [5/16 in] in the horizontal or overhead positions

(3) 12 mm [1/2 in] in the vertical position

6.6.7 Maximum Fill Pass Thickness. The maximum thickness of layers subsequent to root passes of groove and fillet welds shall be as follows:

(1) 3 mm [1/8 in] for subsequent layers of welds made in the flat position

(2) 5 mm [3/16 in] for subsequent layers of welds made in the vertical, overhead, or horizontal positions

6.6.8 Vertical Progression. The progression for all passes in the vertical position shall be upward, unless a downward progression is qualified by tests approved by the Engineer.

6.6.9 CJP Backgouging. CJP groove welds made without the use of steel backing shall have the root gouged to sound metal before welding is started from the second side.

Part C
Submerged Arc Welding (SAW)

6.7 General Requirements

6.7.1 SAW Electrodes. SAW may be performed with one or more single electrodes, one or more parallel electrodes, or combinations of single and parallel electrodes. The spacing between arcs shall be such that the slag cover over the weld metal produced by a leading arc does not cool sufficiently to prevent the proper weld deposit of a following electrode. SAW with multiple electrodes may be used for any groove or fillet weld pass.

6.7.2 WPS Limitations. All welding of quenched and tempered steels shall be performed in compliance with the steel producer's recommendations for maximum allowable combinations of heat input, preheat, and interpass temperature. Such considerations shall include the additional heat input produced during the simultaneous welding of two sides of a common member.

6.7.3 Surface Preparation. Surfaces on which SAW are to be deposited and adjacent faying surfaces shall be clean and free of moisture as specified in 5.2.4.

6.7.4 Penetration. When the joint to be welded requires specific root penetration and is not backgouged, the Contractor shall prepare a sample joint and macroetched cross section to demonstrate that the proposed WPS will attain the required root penetration. The Engineer may accept a radiograph of a test joint or recorded evidence in lieu of the test specified in this subclause. (The Engineer should accept properly documented evidence of previous qualification tests.)

6.7.5 Backing. Roots of groove welds may be made against fused steel backing or approved unfused backing. Roots of fillet welds may be supported by backing to prevent melting-through of the base metal. All backing shall conform to the requirements of 5.13.

6.7.6 Depth-to-Width Ratio. Neither the depth nor the maximum width in the cross section of weld metal deposited in each weld pass shall exceed the width at the surface of the weld pass (see Figure 6.1). This requirement may be waived only if the testing of a WPS to the satisfaction of the Engineer has demonstrated that such welds exhibit freedom from cracks, and the same WPS and electrode-flux combinations are used in construction.

6.7.7 Tack Welds. Tack welds (in the form of fillet welds) 8 mm [5/16 in] or smaller may remain in the roots of joints requiring specific root penetration but shall not produce objectionable changes in the appearance of the weld surface nor result in decreased penetration. Tack welds not conforming to the preceding requirements shall be removed or reduced in size by any suitable means before welding. Tack welds in the root of a joint with steel backing less than 8 mm [5/16 in] thick shall be removed or made continuous for the full length of the joint, using SMAW with low-hydrogen electrodes.

6.8 Electrodes and Fluxes for SAW

6.8.1 Electrodes and Fluxes. Bare electrodes and flux used in combination for SAW of steels shall conform to the requirements of the latest edition of AWS A5.17/A5.17M, *Specification for Carbon Steel Electrodes and Fluxes for Submerged Arc Welding*, or to the requirements of the latest edition of AWS A5.23/A5.23M, *Specification for Low-Alloy Steel Electrodes and Fluxes for Submerged Arc Welding*.

6.8.2 Condition of Flux. Flux used for SAW shall be dry and free of contamination from dirt, mill scale, or other foreign material. All flux shall be purchased in packages that can be stored, under normal conditions, for at least six months without such storage affecting its welding characteristics or weld properties. Flux from damaged packages shall be discarded or shall be dried at a minimum temperature of 260°C [500°F] for one hour before use.

Flux shall be placed in the dispensing system immediately upon opening a package, or, if used from an open package, the flux shall be dried or the top 25 mm [1 in] shall be discarded. All flux in hoppers and other delivery systems open to the atmosphere shall be removed and replaced with new, or freshly dried flux, whenever welding operations have not been conducted for more than 24 hours. All flux in pressurized tanks, flux recovery systems, and other delivery systems closed to the atmosphere shall be removed and replaced with new or freshly dried flux, whenever welding operations have not been conducted for more than 96 hours. Flux that has come in direct contact with water shall not be used.

6.8.3 Flux Reclamation. SAW flux that has not been melted during the welding operation may be reused after recovery by vacuuming, use of catch pans, sweeping from weldment surfaces or other means. Recovered flux shall be passed through an appropriate screen and over a suitable magnet to remove unwanted particles and materials before being returned to the flux supply system. Flux that is not reclaimed from weldment surfaces within one hour of being deposited on the weld shall be dried before being used as provided in 6.8.2.

The Contractor shall have a system for collecting unmelted flux, mixing with new flux as required, and welding with a mixture of these two such that the flux composition and particle size distribution at the arc are relatively constant. Flux fused in welding shall not be reused.

6.9 Procedures for SAW with a Single Electrode

6.9.1 Position. All submerged arc welds shall be made in the flat or horizontal position.

6.9.2 WPS Limits. For procedures qualified in accordance with 7.12.1 or 7.12.2, the following limits shall apply:

6.9.2.1 The maximum welding current to be used in making a groove weld for any pass that has fusion to both faces of the groove shall be 600 A.

6.9.2.2 The maximum current to be used for making fillet welds in the flat position shall be 1000 A.

6.9.3 Maximum Layer Thickness and Width. The thickness of weld layers, except root and surface layers, shall not exceed 6 mm [1/4 in]. When the root opening is 12 mm [1/2 in] or greater, a multiple-pass, split-layer technique shall be used. The split-layer technique shall also be used in making multiple-pass welds when the width of the layer exceeds 16 mm [5/8 in].

6.10 Procedures for SAW with Parallel and Multiple Electrodes

6.10.1 Weld Layer Width. When the width of a surface in a groove on which a layer of weld metal is to be deposited exceeds 12 mm [1/2 in], a split-layer technique shall be used to assure adequate corner fusion. If parallel electrodes are used, the electrodes may be displaced laterally instead of using a split-layer technique. When the width of a previously deposited layer exceeds 25 mm [1 in] for multiple electrodes or 16 mm [5/8 in] for parallel electrodes, and only two electrodes are used, a split-layer technique with electrodes in tandem shall be employed.

6.10.2 Weld Layer Thickness. The thickness of weld layers shall not be limited.

6.10.3 GMAW Root Pass. Parallel and multiple electrode welds may also be made using GMAW in the root of groove or fillet welds followed by single or multiple submerged arcs, provided that the GMAW conforms to the requirements of Part D of Clause 6.

6.10.4 Preheat and Interpass Temperatures. Preheat and interpass temperatures for multiple electrode SAW shall be selected in conformance with 6.2. For single-pass groove or fillet welds, for combinations of metals being welded and the heat input involved, and with the approval of the Engineer, preheat and interpass temperatures may be established which are sufficient to reduce the hardness in the HAZ of the base metal to less than 225 Vickers hardness number for steel having a minimum specified tensile strength not exceeding 415 MPa [60 ksi], and to less than 280 Vickers hardness number for steel having a minimum specified tensile strength greater than 415 MPa [60 ksi] but not exceeding 485 MPa [70 ksi].

The Vickers hardness number shall be determined in conformance with ASTM E384. If another method of hardness is to be used, the equivalent hardness number shall be determined from ASTM E140, and testing shall be performed according to the applicable ASTM specification.

6.10.4.1 HAZ Hardness Determination. When required by 6.10.4, hardness of the HAZ shall be determined:

(1) On the initial macroetch cross sections of a sample test specimen, and

(2) On the surface of the member during the progress of the work. The surface shall be finished as necessary for performance and accurate interpretation of hardness testing.

(a) The frequency of such HAZ testing shall be at least one test area per weldment on the thicker base metal involved in a joint for each 15 m [45 ft] of groove welds or pair of fillet welds.

(b) These hardness determinations may be discontinued after the procedure has been established to the satisfaction of the Engineer.

6.10.4.2 Fillet Welds. Reduction of the preheat requirements of 6.2 shall be prohibited for fillet welds 10 mm [3/8 in] and under in size.

Part D
Gas Metal Arc Welding (GMAW) and Flux Cored Arc Welding (FCAW)

6.11 GMAW/FCAW Electrodes

The electrodes and shielding for GMAW or FCAW for producing weld metal with minimum specified yield strengths of 415 MPa [60 ksi] or less, shall conform to the requirements of the latest edition of AWS A5.18/A5.18M, *Specification for Carbon Steel Electrodes and Rods for Gas Shielded Arc Welding*, AWS A5.20/A5.20M, *Specification for Carbon Steel Electrodes for Flux Cored Arc Welding*, or AWS A5.29/A5.29M, *Specification for Low-Alloy Steel Electrodes for Flux Cored Arc Welding*, as applicable.

6.12 Shielding Gas

A gas or gas mixture used for shielding in GMAW or when required for FCAW shall conform to the requirements of the latest edition of AWS A5.32/A5.32M, *Specification for Welding Shielding Gases*. When requested by the Engineer, the Contractor or fabricator shall furnish the gas manufacturer's certification that the gas or gas mixture is suitable for the intended application and shall meet the dew point requirement.

6.13 Procedures for GMAW and FCAW with a Single Electrode

6.13.1 General. The following are general requirements:

6.13.1.1 Electrode Condition. Electrodes shall be dry and in suitable condition for use.

6.13.1.2 Maximum Electrode Diameter. The maximum electrode diameter shall be 4.0 mm [5/32 in] for the flat and horizontal positions, 2.4 mm [3/32 in] for the vertical position, and 2.0 mm [5/64 in] for the overhead position.

6.13.1.3 Maximum Single Pass Fillet Weld Size. The maximum size of a fillet weld made in one pass shall be 12 mm [1/2 in] for the flat and vertical positions, 10 mm [3/8 in] for the horizontal position, and 8 mm [5/16 in] for the overhead position.

6.13.1.4 Maximum Layer Thickness and Width— GMAW. The thickness of weld layers in groove welds, except root and surface layers, shall not exceed 6 mm [1/4 in]. When the root opening is 12 mm [1/2 in] or greater, a multiple-pass split-layer technique shall be used. The split-layer technique shall also be used in making all multiple-pass welds when the width of the layer exceeds 16 mm [5/8 in].

6.13.1.5 Maximum Layer Thickness and Width— FCAW. The thickness of the weld layers in groove welds, except root and surface layers, shall not exceed 6 mm [1/4 in]. When the root opening is 12 mm [1/2 in] or greater, a multiple-pass split-layer technique shall be used. When the width of a layer of a groove weld in the flat, horizontal, or overhead position is 16 mm [5/8 in] or greater, a multiple-pass split-layer technique shall be used. When welding in the vertical position, a split-layer technique shall be used when the width of the layer exceeds 25 mm [1 in].

6.13.1.6 **WPS.** The welding current, arc voltage, gas flow, mode of metal transfer, and speed of travel shall be such that each pass has complete fusion with adjacent base metal and weld metal, and there is no overlap or excessive porosity or undercutting.

6.13.1.7 **Vertical Progression.** The progression for all passes of vertical position welding shall be upwards, unless a downward progression shall be qualified by tests approved by the Engineer.

6.13.2 **CJP Backgouging.** CJP groove welds made without the use of backing shall have the root of the initial weld gouged, chipped, or otherwise removed to sound weld metal before welding is started from the second side.

6.13.3 **Maximum Wind Velocity.** GMAW, or FCAW-G, shall not be done in a draft or wind unless the weld is protected by a shelter. Such shelter shall be of material and shape appropriate to reduce wind velocity in the vicinity of the weld to a maximum of 8 km/hr [5 mph].

6.13.4 **GMAW Short-Circuiting Process.** GMAW-S shall not be used in the construction of bridge members without the written approval of the Engineer (see Annex M for informative guidelines in determining GMAW-S).

Part E
Electrogas Welding (EGW)

6.14 Qualification of Process, WPSs, and Joint Details

6.14.1 Prior to use, the Contractor shall prepare and qualify each WPS to be used according to the requirements in 7.13. The WPS shall include the joint details, filler metal type and diameter, amperage, voltage (type and polarity), speed of vertical travel if not an automatic function of arc length or deposition rate, oscillation (traverse speed, length, and dwell time), type of shielding including flow rate and dew point of gas (if required), or type of flux, type of molding shoe, postweld heat treatment if used, and other pertinent information.

6.14.2 The EGW process shall not be used for welding quenched and tempered steel nor for welding components of members subject to tensile stresses or reversal of stress.

6.15 Condition of Electrodes and Guide Tubes

Electrodes and guide tubes shall be dry, clean, and in suitable condition for use.

6.16 Shielding Gas

A gas or gas mixture when required for shielding of EGW shall conform to the requirements of the latest edition of AWS A5.32/A5.32M, *Specification for Welding Shielding Gases*. When requested by the Engineer, the Contractor or fabricator shall furnish the gas manufacturer's certification that the gas or gas mixture is suitable for the intended application and will meet the dew point requirements.

6.17 Procedures for EGW

6.17.1 Gas to be used for shielding shall be of a welding grade and shall meet all requirements of the WPS. When mixed at the welding site, suitable meters shall be used for proportioning the gases. Percentage of gases shall conform to the requirements of the WPS.

6.17.2 EGW that requires external gas shielding shall not be done in a draft or wind of a velocity greater than 8 km/hr [5 mph] unless the weld is protected by a shelter. This shelter shall be of a material and shape appropriate to reduce wind velocity in the vicinity of the weld surface to a maximum of 8 km/hr [5 mph].

6.17.3 The type and diameter of the electrodes used shall meet the requirements of the WPS. Electrodes shall be selected from Table 6.1.

6.17.4 Welds shall be started in such a manner as to allow sufficient heat buildup for complete fusion of the weld metal to the groove faces of the joint before the weld leaves the sump. Welds that have been stopped at any point in the weld joint long enough for the slag or weld pool to begin to solidify may be restarted and completed, provided the completed weld is proven satisfactory after examination by UT of at least 150 mm [6 in] on either side of the restart and, unless prohibited by joint geometry, the weld soundness shall also be confirmed by RT. All such restart locations shall be recorded and reported to the Engineer.

6.17.5 Preheat is not required for EGW. However, the temperature of the base metal at the point of welding shall be above the atmospheric dew point.

6.17.6 All groove welds in butt joints in main members shall be radiographed in conformance with the provisions of Clause 8, Parts B and C, and shall conform to the requirements of 8.26 and Figure 8.8.

6.17.7 Welds having discontinuities prohibited by 8.26 shall be repaired as allowed by 5.7, using a qualified welding process, or the entire weld shall be removed and replaced.

Part F
Electroslag Welding (ESW)

6.18 Qualification of Process, WPSs, and Joint Details

6.18.1 Prior to use, the Contractor shall prepare and qualify each WPS to be used according to the requirements in 7.14.

6.18.2 The WPS for ESW shall include:

(1) Consumable guide configuration and material specification used for the consumable guide

(2) Number of electrodes

(3) flux type, amount of flux added before the start of welding, and subsequent flux feed rate

(4) Joint details, including plate thickness(es)

(5) Base metal

(6) Electrode designation, composition, diameter, manufacturer, product name

(7) Wire feed speed

(8) Type and polarity of current

(9) Voltage

(10) Details of reinforcement groove dimensions of water-cooled copper shoes and coolant flow rate

(11) Type of sealing material used to prevent slag run-outs

(12) Accessories used within the weld zone, including consumable guide electrical insulators.

6.18.3 ESW may be used for welding components of members subject to tensile stresses or reversal of stress only when application is limited to service temperatures of –35°C [–30°F] and above (AASHTO Temperature Zones I and II). ESW shall not be used for fracture-critical members or components, for quenched and tempered steel (Q&T), or thermo-mechanical control processed steel (TMCP).

6.19 Condition of Electrodes and Consumable Guides

6.19.1 Electrodes. Electrodes shall be kept dry and free of contamination from dirt, grease, rust, or other foreign material. Electrodes shall be received and stored in moisture-resistant packages that are undamaged and shall be protected against contamination and injury during shipment, storage, and use. Electrode packages shall remain effectively sealed against moisture until the electrode is required for use. When removed from protective packaging and installed on machines, care shall be taken to protect the electrodes from deterioration or damage. When welding is to be suspended for more than eight hours, electrodes shall be protected on the machine or removed and stored, as recommended by the manufacturer. Electrodes from packages damaged in transit or in handling prior to opening shall not be used.

6.19.2 Consumable Guides. Consumable guides shall be kept dry and free of contamination from dirt, grease, rust, or other foreign material, and be in suitable condition for use.

6.20 Condition of Flux

Flux shall conform to all of the following requirements:

(1) Flux shall be neutral flux.

(2) Flux shall be dry and free of contamination from dirt, grease, mill scale, or other foreign material.

(3) Flux shall be received in moisture-resistant packaging that can be stored under normal conditions for at least six months without such storage affecting its welding characteristics or weld properties.

(4) Flux shall be conditioned at 120°C [250°F] for at least two hours prior to welding, or as recommended by the manufacturer, and stored at the same temperature until dispensed for use.

(5) Flux that has been dispensed for use shall be discarded after 8 hours.

(6) Flux from packages damaged in transit or in handling shall be discarded.

(7) Flux that has been wet shall not be used.

6.21 Consumable Guide Electrical Insulators

Insulators shall be used to maintain the position of the consumable guide within the weld groove. Insulators shall be kept dry and free of contamination from dirt, grease, or other foreign material.

6.22 Procedures for ESW

6.22.1 Surfaces of the plate within 25 mm [1 in] of the weld joint and all surfaces on which weld metal will be deposited shall be free of any mill scale, rust, or other contaminants. The groove preparation shall be square with a root opening of 19 mm ± 3 mm [3/4 in ± 1/8 in].

6.22.2 Materials for consumable guides shall be of the composition described in Annex H. The configuration of consumable guides is an essential variable. Consumable guides shall be delivered from the manufacturer in moisture-resistant packaging. After removal from that package, they shall be protected and stored to remain free of rust, moisture, or any other contaminants.

The distance from the edge of the consumable guide to the surface of the cooling shoe shall be no less than 6 mm [1/4 in] nor greater than 16 mm [5/8 in]. The distance from the surface of the cooling shoe to the center of the hole in the guide for the electrode shall be no less than 12 mm [1/2 in] nor greater than 32 mm [1-1/4 in]. For consumable guides designed for multiple electrodes, the electrode separation (center to center) shall not exceed 50 mm [2 in].

6.22.3 The electrode wire passage shall have a maximum diameter or width of 3.0 mm [1/8 in] for 2.4 mm [3/32 in] diameter electrode wire and 2.4 mm [3/32 in] for 1.6 mm [1/16 in] diameter electrode wire.

6.22.4 The starting sump depth shall be no less than 75 mm [3 in] or the thickness of the plate, whichever is greater. Tack welds securing steel sumps and run-off tabs shall be:

(1) within the joint to be remelted and incorporated during welding,

(2) on permanent base metal outside the weld zone and subsequently removed along with a 3 mm [1/8 in] deep layer of the base metal under the tack weld, or

(3) on portions of base metal that will be removed and discarded after welding.

6.22.5 Retaining shoes shall be water-cooled and made of copper. Shoes shall fit tightly to the plate surface to prevent slag leakage. Only dry refractory material may be used for filling shoe-to-plate gaps. Water-based sealers shall be limited to reinforcing previously placed dry sealer along the outside edges of the shoes to prevent slag leakage.

Shoes along one side of the weld may be plumbed in series, but each side shall be plumbed separately; the water from the shoes on one side shall not be cycled directly into the copper shoes on the other side of the weld joint before the water is cooled. Minimum flow through the shoes shall be 15 L [4 gal] per minute per side. The water temperature rise from the inlet side of the first shoe to the outlet side of the last shoe, for each group of shoes, shall be 3°C to 11°C [5°F to 20°F] on each side. The cooling shoes shall remain in place for a minimum of two minutes after the slag pool advances to the next shoe or upon completion of the weld. The back side (i.e., the face of the plate opposite of the stem) of a T-joint shall have a water-cooled copper shoe to remove the heat from the weld if the plate is less than 50 mm [2 in] thick.

6.22.6 Electrode and flux shall meet the requirements of the WPS and Annex H. The wire diameter for ESW-NG shall be 2.4 mm [3/32 in] or 1.6 mm [1/16 in]. Only metal cored electrodes shall be used for ESW-NG. Solid electrodes shall not be permitted.

6.22.7 Strongbacks (if used to attach retaining shoes) shall not be attached to the base metal by tack welds.

6.22.8 ESW Welding Parameters

6.22.8.1 Voltage. Voltage shall be in accordance with Table 6.7.

6.22.8.2 Travel Speed. Target travel speed (vertical rate of rise) shall be determined using the following formula:

Target Travel Speed (mm/min) = 75 – [0.5 × Thickness]

Target Travel Speed (in/min) = 3 – [0.5 × Thickness]

WPS travel speed shall be between 90% and 125% of target travel speed.

6.22.8.3 Wire Feed Speed. Wire feed speed shall be adjusted as needed to satisfy 6.22.8.1 and 6.22.8.2.

6.22.9 Welding shall be started in such a manner as to permit sufficient heat buildup for complete fusion of the weld metal to the groove faces of the joint before the weld leaves the starting sump. Once welding has begun, welding shall continue uninterrupted for the length of the joint, except as permitted in 6.22.15.

6.22.10 Once the starting arc has been extinguished and the electroslag mode is in progress, flux additions shall be regulated continuously using an automatic feeding device. For monitoring purposes, current and voltage shall be recorded on a continuous current and voltage chart and variations in these readings used to monitor slag depletion.

6.22.11 Preheat is not required. However, the temperature of the base metal at the point of welding shall be above the atmospheric dew point.

6.22.12 Electrode oscillation shall not be permitted.

6.22.13 Inspection shall use both radiographic and ultrasonic methods in accordance with Clause 8.

6.22.14 Welds having defects prohibited by 8.26 shall be repaired or the entire weld shall be removed to at least 3 mm [1/8 in] beyond the widest part of the weld nugget and rewelded. If any portions of detectable defects are within 6 mm [1/4 in] of the weld centerline and their cumulative length is greater than 15% of the weld length (not including the weld tabs), the weld shall not be repaired but shall be completely removed to at least 3 mm [1/8 in] beyond the widest part of the weld nugget and rewelded.

6.22.15 Restarts. Restarts in electroslag welds may be used, providing the point of the restart is clearly marked, and the restart region plus a minimum of 75 mm [3 in] of material above and below the restart are not part of the final completed product.

6.22.16 Interrupted Welds. Should a weld be interrupted, at the Contractor's option, the whole weld may be removed and rewelded with ESW-NG. Alternately, at the Contractor's option, the whole weld may be removed and the joint rewelded with an alternative process approved for use in this code. Removal shall include all of the weld, plus a minimum of 3 mm [1/8 in] beyond the widest part of the weld nugget.

Part G
Plug and Slot Welds

6.23 Plug Welds

The technique used to make plug welds when using SMAW, GMAW (except GMAW-S), and FCAW processes shall be as follows:

6.23.1 **Flat Position.** For welds to be made in the flat position, each weld shall be deposited around the root of the joint and then deposited along a spiral path to the center of the hole, fusing and depositing a layer of weld metal in the root and bottom of the joint. The arc is then carried to the periphery of the hole and the procedure repeated, fusing and depositing successive layers to fill the hole to the required depth. The slag covering the weld metal should be kept molten until the weld is finished. If the arc is broken or the slag is allowed to cool, the slag shall be completely removed before restarting the weld.

6.23.2 **Vertical Position.** For welds to be made in the vertical position, the arc shall be started at the root of the joint at the lower side of the hole and shall be carried upward, fusing into the face of the inner plate and to the side of the hole. The arc shall be stopped at the top of the hole, the slag shall be cleaned off, and the process shall be repeated on the opposite side of the hole. After cleaning slag from the weld, other layers should be similarly deposited to fill the hole to the required depth.

6.23.3 **Overhead Position.** For welds to be made in the overhead position, a spiral procedure shall be followed as for the flat position, except that the slag should be allowed to cool and should be completely removed after depositing each successive layer until the hole shall be filled to the required depth.

6.24 Slot Welds

Slot welds shall be made using techniques similar to those specified in 6.23 for plug welds, except that if the length of the slot exceeds three times the width, or if the slot extends to the edge of the part, the technique requirements of 6.23.3 shall apply.

6.25 Plug and Slot Welds

When plug and slot welds are made by continuous welding over previously deposited weld beads and through molten slag, the welder shall observe the arc and slag cover for signs of conditions that are present during the formation of fusion discontinuities, such as intermittent arc, excessive spatter, and slag boiling with excessive gas. When these signs are observed, the welding shall be discontinued. After the slag has cooled, all slag and fusion defects shall be removed before welding is resumed.

Part H
Control of Production Welding Variables

6.26 Tests

Control of welding variables shall be based on the results of WPS qualification tests performed as described in Clause 7.

6.27 Control of Variables

Welders and welding operators shall set welding controls, weld, and operate welding equipment within the limitations on current, voltage, travel speed, and shielding gas flow rates described in the approved WPS.

6.28 Calibration of Equipment

6.28.1 **Verification.** Equipment used to measure variables shall be accurately calibrated. The Contractor shall verify, at least every 3 months, the accuracy of meters and other devices used to record or display welding variables. The equipment used for verifying meters and other devices shall be certified annually.

6.28.2 Meter Error Correction. Correction charts or similar methods may be used to compensate for meter error when approved by the Engineer.

6.29 Current Control

6.29.1 Wire Feed Speed. The welding current may be controlled by controlling the wire feed speed, provided correlation between amperage and wire feed speed is known for specific electrode types and diameters.

6.29.2 Correlation Data. The Inspector shall have access to accurate amperage versus wire feed speed tables or charts whenever wire feed speed is used as a method of current control.

Table 6.1
Matching Filler Metals for WPSs[a, b, c, d]

Base Metal AASHTO [ASTM] Designation	Welding Processes and AWS Electrode Specification and Classifications						
	SMAW[c]	SAW[e, f]	FCAW-G[e]	FCAW-S[e]	GMAW[e]	ESW-NG	EGW[g]
M 270M/M 270 (A709/A709M) Gr. 250 [36]	**A5.1/A5.1M** E6018 E7015 E7016 E7018 E7018-1 E7018M E7028	**A5.17/A5.17M** F6A0-EXXX F6A0-ECX F7A0-EXXX F7A0-ECX	**A5.20/A5.20M** E7XT-1C, -1M E7XT-5C, -5M E7XT-9C, -9M E7XT-12C, -12M	**A5.20/A5.20M** E7XT-6, -8	**A5.18/A5.18M** ER70S-2, -3, -6, -7 E70C-3C, E70C-3M E70C-6C, E70C-6M	See Annex H	**A5.26/A5.26M** EG60X-X EG62X-X EG70X-X EG72X-X
	A5.5/A5.5M E7015-X E7016-X E7018-X E7015, -16, -18-C1L, -C2L E7018-C3L E7018-W1 E8015-C1, C2, C3, C4 E8016, -18-C1, -C2 E8016, -18-C3, -C4 E8018-W2	**A5.23/A5.23M** F7A0-EXXX-XX F7A0-ECXXX-XX F8A0-EXXX-XX F8A0-ECXXX-XX	**A5.29/A5.29M** E6XT1-NiC, -NiM E7XT1-XC, -XM E7XT5-XC, -XM E8XT1-XC, -XM E8XT1-NiXC, -NiXM E8XT1-W2C, -W2M E8XT5-XC, -XM E8XT5-NiXC, -NiXM	**A5.29/A5.29M** E6XT8-X E7XT4-X E7XT6-X E7XT7-X E7XT8-X E8XT8-X	**A5.28/A5.28M** ER70S-XXX ER80S-XXX ER80S-NiX E70C-XXX E80C-NiX E80C-W2		
M 270M/M 270 (A709/A709M) Gr. 345 [50] Type 1, 2, 3; Gr. 345S [50S];	**A5.1/A5.1M** E7015 E7016 E7018 E7018-1 E7018M E7028	**A5.17/A5.17M** F7A0-EXXX F7A0-ECX	**A5.20/A5.20M** E7XT-1C, -1M E7XT-5C, -5M E7XT-9C, -9M E7XT-12C, -12M	**A5.20/A5.20M** E7XT-6, -8	**A5.18/A5.18M** ER70S-2, -3, -6, -7 E70C-3C, E70C-3M E70C-6C, E70C-6M	See Annex H	**A5.26/A5.26M** EG70X-X EG72X-X
Gr. 345W [50W] (up to 100 mm [4 in] thick); Gr. HPS 345W [HPS 50W][h, i]	**A5.5/A5.5M** E7015-X E7016-X E7018-X E7015, -16-C1L, -C2L E7018-C1L, -C2L, -C3L E7018-W1 E8015-C1, C2, C3, C4 E8016, -18-C1, -C2 E8016, -18-C3, -C4 E8018-W2	**A5.23/A5.23M** F7A0-EXXX-XX F7A0-ECXXX-XX F8A0-EXXX-XX F8A0-ECXXX-XX	**A5.29/A5.29M** E7XT1-XC, -XM E7XT5-XC, -XM E8XT1-XC, -XM E8XT1-NiXC, -NiXM E8XT1-W2C, -W2M E8XT5-XC, -XM E8XT5-NiXC, -NiXM	**A5.29/A5.29M** E7XT-X E7XT6-X E7XT7-X E7XT8-X E8XT8-X	**A5.28/A5.28M** ER70S-XXX ER80S-XXX ER80S-NiX E70C-XXX E80C-NiX E80C-W2 E80C-XXX		

(Continued)

Table 6.1 (Continued)
Matching Filler Metals for WPSs[a, b, c, d]

Base Metal AASHTO [ASTM] Designation	SMAW[e]	SAW[e, f]	FCAW-G[e]	FCAW-S[e]	GMAW[e]	ESW-NG	EGW[g]
	Welding Processes and AWS Electrode Specification and Classifications						
M 270M/M 270 (A709/A709M) Gr. HPS 485W [HPS 70W][h, j]	**A5.5/A5.5M** E9018M	**A5.23/A5.23M** F9A0-EXXX-XX F9A0-ECXXX-XX F9A2-EXXX-XX F9A2-ECXXX-XX	**A5.29/A5.29M** E9XT1-XC, -XM E9XT5-XC, -XM	**A5.29/A5.29M** E9XT8-X	**A5.28/A5.28M** E90C-K3 ER90S-XXX ER90C-XXX	Not Authorized	Not Authorized
M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W] Over 60 mm [2-1/2 in] thick[h]	**A5.5/A5.5M** E10010M E11018M	**A5.23/A5.23M** F10A4-EXXX-XX F10A4-ECXXX-XX F11A4-EXXX-XX F11A4-ECXXX-XX	**A5.29/A5.29M** E10XT1-XC, -XM E10XT5-XC, -XM E11XT1-XC, -XM E11XT5-XC, -XM	No A5.29/A5.29M Class available at this time	**A5.28/A5.28M** E100C-K3 E110C-K3, -K4 ER100S-1 ER100S-2 E100C-XXX E110C-XXX ER100S-XXX ER110S-XXX	Not Authorized	Not Authorized
M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W] 60 mm [2-1/2 in] thick or less[h]	**A5.5/A5.5M** E11018M	**A5.23/A5.23M** F11A4-EXXX-XX F11A4-ECXXX-XX	**A5.29/A5.29M** E11XT1-XC, -XM E11XT5-XC, -XM	No A5.29/A5.29M Class available at this time	**A5.28/A5.28M** E110C-K3, K4 E110C-XXX ER110S-XXX ER110S-1	Not Authorized	Not Authorized

[a] When welds are to be stress-relieved, the weld metal shall not exceed 0.05% vanadium.

[b] All listed values are minimums unless a range is shown.

[c] See 7.5.1 for filler metal qualification requirements.

[d] AWS A5.XXM specification (where "XX" refers to a particular filler metal document using SI units) electrodes of the same classification may be used in lieu of the AWS A5.XX specification (where "XX" refers to a particular filler metal document using U.S. Customary Units) electrode classification.

[e] Filler metals for alloy groups B3, B3L, B4, B4L, B5, B5L, B6, B6L, B7, B7L, B8, B8L, or B9 in AWS A5.5/A5.5M, A5.23/A5.23M, A5.28/A5.28M, and A5.29/A5.29M shall be prohibited in the aswelded condition.

[f] Electrode specifications with the same yield and tensile properties, but with lower impact test temperature, may be substituted. (e.g., F7A2-EXXX may be substituted for F7A0-EXXX).

[g] Not authorized for tension and reversal members.

[h] Special welding materials and procedures may be required to match atmospheric, corrosion, and weathering characteristics (see Table 6.2 for M 270M/M 270 (A709/A709M) Gr. 345W [50W] and Gr. HPS 345W [HPS 50W] steels). Filler metal with suitable weathering characteristics for bare unpainted applications of M 270M/M 270 (A709/A709M) Gr. HPS 690W [HPS 100W] and M 270M/M 270 (A709/A709M) Gr. HPS 485W [HPS 70W] steels shall be approved by the Engineer.

[i] The 550 MPa [80 ksi] filler metals (e.g., E80XX, F8AX-XXXX) are intended for exposed applications of weathering steels. They need not be used on applications of M 270M/M 270 (A709/A709M) Gr. 345W [50W] or Gr. HPS 345W [HPS 50W] that will be painted.

[j] When joining HPS 485W [HPS 70W], the weld deposit shall have a minimum content of 0.8% nickel as determined by A5.XX filler metal tests.

Table 6.2
Filler Metal Requirements for Exposed Bare Application of M 270M/M 270 (A709/A709M) Gr. 345W [50W] and Gr. HPS 345W [HPS 50W] Steels

Process	AWS Filler Metal Specification	Approved Electrodes
SMAW	A5.5/A5.5M	All electrodes that deposit weld metal meeting a C1, C1L, C2, C2L, C3, W1, or W2 analysis
SAW	A5.23/A5.23M	All electrode-flux combinations that deposit weld metal with a Ni1, Ni2, Ni3, Ni4, or W analysis
FCAW	A5.29/A5.29M	All electrodes that deposit weld metal with a Ni1, Ni2, Ni3, Ni4, or W analysis
GMAW	A5.28/A5.28M	All electrodes that meet filler metal composition requirements of Ni1, Ni2, Ni3, or W2 analysis

Notes:
1. This is a partial listing which does not cover EGW or ESW of M 270M/M 270 (A709/A709M) Gr. 345W [50W] or Gr. HPS 345W [HPS 50W] steel and makes no provision for other steels with weathering characteristics such as M 270M/M 270 (A709/A709M) Grade HPS 485W [HPS 70W] and Grade HPS 690W [HPS 100W] steels. The Engineer shall approve all filler metal to be used in exposed, unpainted applications not covered by this table. The chemical composition of weld metal deposited by the electrodes listed in this table may be used as a guide to weld metal chemical composition considered acceptable in weathering applications. There is considerable dilution of base metal in ESW and EGW; therefore, the weld deposit will not match the electrode or base metal chemical composition.
2. See 7.5.1 for filler metal qualification requirements.
3. AWS A5.XXM specification (where "XX" refers to a particular filler metal document using SI units) electrodes of the same classification may be used in lieu of the AWS A5.XX specification (where "XX" refers to a particular filler metal document using U.S. Customary Units) electrode classification.

Table 6.3
Minimum Preheat and Interpass Temperature, °C [°F]

Welding Process (Base Metal)	To 20 mm [3/4 in] Incl.	Thickness of Thickest Part at Point of Welding, mm [in]: Over 20 mm [3/4 in] to 40 mm [1-1/2 in] Incl.	Over 40 mm [1-1/2 in] to 65 mm [2-1/2 in] Incl.	Over 65 mm [2-1/2 in]
SAW; GMAW; FCAW; SMAW (M 270M/M 270 (A709/A709M) Gr. 250 [36], 345 [50], 345S [50S], 345W [50W], HPS 345W [HPS 50W])	10 [50]	20 [70]	65 [150]	110 [225]
SAW; GMAW; FCAW; SMAW (M 270M/M 270 (A709/A709M) Gr. HPS 485W [HPS 70W] and HPS 690W [HPS 100W]	10 [50]	50 [125]	80 [175]	110 [225]

[a] See 6.2.2 for maximum preheat and interpass temperature limitations.

Note: See Annex F and Tables 12.4, 12.5, 12.6, 12.7, and 12.8. for alternate preheat and interpass temperatures.

Table 6.4
Minimum Holding Time (see 6.4.2)

6 mm [1/4 in] or Less	Over 6 mm [1/4 in] Through 50 mm [2 in]	Over 50 mm [2 in]
15 minutes	4 minutes/2 mm [1/16 in]	2 hr. plus 15 minutes for each additional 25 mm over 50 mm [1 in over 2 in]

Table 6.5
Alternate Stress-Relief Heat Treatment (see 6.4.3)

Decrease in Temperature Below Minimum Specified Temperature, ∆°C [°F]	Minimum Holding Time at Decreased Temperature, Hours per 25 mm [1 in] of Thickness
30 [50]	2
60 [100]	3
90 [150]	5
120 [200]	10

Table 6.6
Allowable Atmospheric Exposure of Low-Hydrogen SMAW Electrodes

AWS Filler Metal Specification	Electrode	Hours[a]
A5.1	E70XX	4 max.
A5.5	E70XX-X	4 max.
	E80XX-X	2 max.
	E90XX-X	1 max.
	E100XX-X	1/2 max.
	E110XX-X	1/2 max.

[a] See 6.5.2.3

Table 6.7
Required Voltage for ESW

Wire Diameter	Single Wire	Two Wires
2.4 mm [3/32 in]	33 V–37 V	31 V–36 V
1.6 mm [1/16 in]	29 V–35 V	28 V–33 V

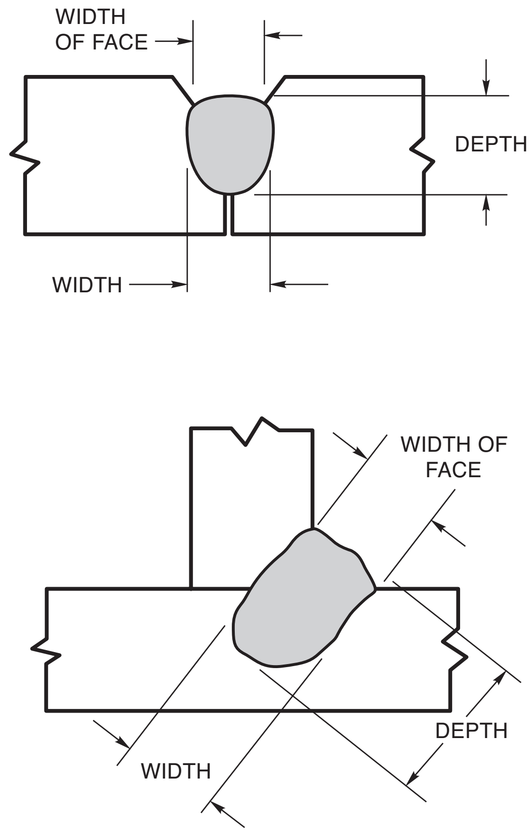


Figure 6.1—Weld Bead in Which Depth and Width Exceed the Width of the Weld Face (see 6.7.6)

7. Qualification

7.0 Scope

Qualification of a Welding Procedure Specification (WPS) is covered in Part A. Qualification of welding personnel (i.e., welders, welding operators, and tack welders) is covered by Part B.

Part A
Welding Procedure Specification (WPS) Qualification

7.1 Approval

Approval of WPSs shall be based on prequalification or qualification in accordance with the requirements of Part A of this clause.

7.1.1 Purpose of WPS Qualification Tests. The WPS qualification tests required by this code are designed to provide assurance that the weld metal produced by welding in conformance with the provisions of this code shall produce weld metal strength, ductility, and toughness conforming to Table 7.3.

7.2 Qualification Responsibility

Each Contractor shall conduct tests to qualify or verify WPSs as required by this code (see 7.10, 7.12, 7.13, and 7.14 for WPS qualification requirements).

7.2.1 Acceptance Requirements. Acceptance of WPS qualification tests shall be as described in 7.2.3 and 7.3.

7.2.2 Contractor. The Contractor shall prepare WPSs, based upon the parameter limitations imposed by Part A of this clause, and, within these limits, shall specify welding variables that will produce the welding conditions, characteristics, weld sizes, and contours required in the work.

7.2.3 Previous Qualification. The Engineer may accept previous qualification tests of welders, welding operators, and tack welders, provided the tests are properly documented and meet the requirements of this code.

The Engineer may accept evidence of previous WPS or pretest and verification qualification testing, provided (1) the PQR (procedure qualification record) is complete and shows compliance with the requirements of these specifications, and (2) the results of the tests are certified as accurate by a state representative or an independent third party acceptable to the state.

7.2.4 Excess Testing. Testing in excess of that required by this code shall be paid for by the Owner at prices established by agreement with the Contractor unless otherwise provided in the contract documents. Irrespective of this requirement, the Engineer may order tests of welders, welding operators, or WPSs whenever there is evidence that unacceptable welds are being or have been produced.

7.2.5 Records. Records of the test results shall be kept by the Contractor/fabricator/erector and shall be made available to those authorized to examine them.

7.3 Duration

All approved PQRs are valid indefinitely unless application of the WPS results in consistently substandard welds.

7.4 Base Metal

The following provisions cover the base metal to be used for WPS qualification, pretest, and verification tests.

7.4.1 Base-Metal Qualification Requirements. For qualification of WPSs for approved base metals listed in 1.2.2, The filler metal, base metal, and backing used in the qualification test shall conform to Table 7.1, which lists the base materials that may be used in the test for a given production filler metal and base metal.

Equivalent ASTM steels shall be permitted for use as qualification test plates in accordance with Table 7.2.

7.4.2 Use of Unlisted Base Metals. When a steel other than one of those described in 1.2.2 is approved under the provisions of the general specification, and such steel is proposed for welded construction under this code, WPSs shall be established by qualification in conformance with the requirements of 7.12.4, with qualification tests using the specified base metal and the electrode to be used in production. The fabricator shall have the responsibility for establishing the WPS by qualification. Testing requirements shall be as specified in the contract documents or as approved by the Engineer.

7.4.2.1 The Engineer shall require evidence of adequate weldability of the steel, which as a minimum shall require the following:

(1) Acceptance by other national codes such as ASME, AWS (Offshore Applications), and ABS (Ships) of the steel for similar or stricter requirements for strength and toughness at equivalent loading rates.

(2) A minimum history of five-year use under similar conditions of loading.

(3) Records of past weld testing that would verify adequate resistance of the steel to hydrogen cracking at medium restraint levels. These tests should also establish the maximum and minimum heat input range for each welding process to be used in construction.

7.4.2.2 The responsibility for determining weldability, including the assumption of additional testing costs involved, shall be assigned to the party who either specifies a material not described in 1.2.2, or who proposes the use of a substitute material not described in 1.2.2. The party proposing the use of a substitute material not described in 1.2.2 shall assume the additional costs involved in establishing the WPS as required in 7.4.2.

7.4.2.3 When base metals not described in 1.2.2, are approved for welding to base metals of the same specification and grade or to steels described in 1.2.2, the welding procedure shall be qualified by test under the provisions of 7.12.4.

(1) In addition, when specified in the contract documents or ordered by the Engineer, CVN tests shall be made to measure the toughness of the coarse-grained area of the HAZ (see 7.4.2.5).

(2) The WPS shall list all welding variables and the minimum preheat and interpass temperature for the thicknesses listed in Table 6.3.

(a) When quenched and tempered steels are to be welded, both the minimum and maximum preheat and interpass temperatures shall be listed for each welding heat input and thickness as shown in Table 12.8.

(b) The WPS shall list any special precautions necessary to avoid weld and HAZ cracking and to ensure that the required strength, ductility, and toughness will be produced.

7.4.2.4 Unlisted Steels with $F_y \geq$ 485 MPa [70 ksi]. WPSs used to produce matching weld metal to join steels, with a minimum specified yield strength of 485 MPa [70 ksi] or greater that are not described in 1.2.2, shall be qualified by the Contractor as specified in the contract documents or ordered by the Engineer in conformance with 7.4.2. Weldability testing shall be as determined by the Engineer, or approved by AASHTO.

7.4.2.5 Charpy V-Notch (CVN) Test Requirements. WPS qualification tests for welds on steels with minimum specified yield strength of 485 MPa [70 ksi] or greater shall measure strength, ductility, toughness, and soundness of the weld metal. When specified in the contract documents, qualification tests for steels shall also measure the CVN test values of the coarse grained area of the HAZ. The minimum CVN test energy, test temperature, orientation of the notch, and other necessary details shall be specified in the contract documents when HAZ testing is required.

7.4.3 CMTRs. Copies of certified mill test reports (CMTRs) shall be furnished for all plates and backing used in testing.

7.5 Welding Consumables

Welding consumables shall conform to the provisions of the appropriate filler metal specifications described in Table 6.1 or other specification approved by the Engineer. Filler metal tests of conformance shall be conducted by the manufacturers of welding consumables, as required by the specifications. The tests shall conform to the requirements for the electrode, electrode-flux combination, or electrode–shielding gas combination, as specified to match the base metal to be welded, unless otherwise specified in the contract documents. Tests shall be conducted annually unless otherwise specified, and certification shall be as specified in Clause 6.

7.5.1 WPS Requirements for Consumables. See Table 7.4 for the WPS qualification requirements for consumables.

If the name of a manufacturer changes (e.g., merger or acquisition) or if the brand name or type of a consumable is revised without reformulation or other physical changes, such changes shall not constitute a change that requires WPS requalification. New WPSs may use the new identity based upon a PQR retaining the old information. Existing WPSs shall be revised to list the new identity while based upon a PQR retaining the old information. Documentation from the manufacturer explaining the change shall be filed with the PQR.

7.5.2 Active Flux. WPSs that use active fluxes shall be limited to single- and two-pass applications, unless the WPS is qualified under the provisions of 7.12.4 and approved by the Engineer.

7.5.3 Undermatching Filler Metal. When specified in shop drawings, undermatching filler metal shall be used. Qualifications of WPSs using undermatching filler metal shall conform to 7.7.9.

7.6 Test Plate Thickness

7.6.1 Groove weld qualification tests for WPSs that use SMAW, FCAW, GMAW, and SAW shall be conducted on plates that are 25 mm [1 in] thick or greater.

7.6.2 EGW and ESW WPSs. Test plates shall conform to Table 7.7 (17).

7.6.3 Fillet Weld Soundness Tests. Fillet weld soundness test plate thickness shall conform to Figure 7.8.

7.7 General Requirements for WPS Qualification

7.7.1 WPS Qualification. Except as exempted by 1.3.7 or 7.11, groove weld WPSs shall be qualified in accordance with 7.12, 7.13 or 7.14, and fillet weld WPSs shall be qualified in accordance with 7.10. Figure 7.1 shall be used for qualification testing of WPSs under 7.12. Groove WPSs qualified or prequalified by 1.3.7, 7.11, or 7.12 may be used with joint details in Figures 4.4 or 4.5 without further testing.

7.7.2 Pretest. A WPS pretest is a WPS qualification test performed in conformance with 7.12 or 7.13 by someone other than the Contractor, but used by the Contractor as a basis for preparing WPSs. Figure 7.1 shall be used for all pretesting qualification. Pretests shall not be used to qualify ESW procedures.

7.7.3 Verification of PQRs. A verification test is a simplified version of a qualification test that shall be performed by the Contractor when using a Procedure Qualification Test Record provided by a third party. Figure 7.2 shall be used for all verification testing.

7.7.4 Exemption from Further Testing. WPSs for groove and fillet welds that have been qualified by test, or pretested and verified as described in this clause, conforming to the requirements of Clauses 4, 5, and 6, shall be exempt from further qualification testing, unless otherwise specified in the contract documents.

7.7.5 Joints Not Conforming to Figure 4.4 or 4.5. When the Contractor uses groove weld details that do not conform to the details of Figure 4.4 or 4.5, the WPSs using these details shall be qualified by test as described in 7.12.4 using Figure 7.3. Bend and tensile tests shall be used to evaluate soundness. The mechanical properties of the weld metal shall be determined by the WPS testing described in 7.12, using Figure 7.1.

Test plates for groove welds in corner or T-joints shall be butt joints having the same groove configuration as the corner or T-joint to be used in construction, except the depth of groove need not exceed 25 mm [1 in].

7.7.6 Aging. No test plate or specimen produced for WPS qualification shall be heat treated, stress relieved, aged at temperatures above room temperature, or modified in any way after welding except by approved machining and testing procedures, unless the treatment is stated as a requirement of the WPS and is a requirement for similar welds in the structure.

7.7.7 Combination of WPSs. With the exception of the provision of 7.7.7.1 involving FCAW-S WPSs, any combination of approved WPSs may be used to complete a single welded joint without further testing, provided the limitations of essential variables applicable to each WPS are observed.

7.7.7.1 Exception. When FCAW-S WPSs are combined with other weld process WPSs, or when combined with FCAW-G, the combination shall be qualified by test. Test Plate A (see Figure 7.1) shall be used and the sequence of the weld layers from the different processes shall be the same as will be employed in production.

Approximately one-third of the thickness of the joint shall be welded with the substrate material so that all weld metal tension test and Charpy impact specimens are taken from an area of maximum dilution, between the weld beads. FCAW-S WPSs may be combined with other FCAW-S WPSs and shall be permitted without testing of the combination.

7.7.8 Previous Code Editions. WPSs qualified to previous editions of this code while those editions were in effect shall be acceptable. The use of earlier editions in lieu of the current edition shall be prohibited for new qualifications, unless the specific earlier edition is specified in the contract documents.

7.7.9 Production WPSs that utilize undermatching filler metal shall be qualified in conformance with 7.12.

7.7.10 Weld Cleaning. Power tools may be used to remove discontinuities identified during the in-process welding of WPS qualification tests. In addition, upon weld test completion, the weld may be made flush by power tools as necessary in order to facilitate testing.

7.8 Position of Test Welds

7.8.1 Qualification Requirements. All welds that will be encountered in actual construction shall be classified as (1) flat, (2) horizontal, (3) vertical, or (4) overhead in conformance with the definitions of welding positions described in Figures 7.4 and 7.5. Each WPS shall be tested in the position in which welding will be performed in the work.

7.8.2 Groove Weld Test Positions. Plates shall be welded in the following positions, except that test welds made in the flat position shall also qualify for the horizontal position:

7.8.2.1 Position 1G (Flat). The test plates shall be placed in an approximately horizontal plane and the weld metal shall be deposited from the upper side (see Figure 7.6 [Detail A]).

7.8.2.2 Position 2G (Horizontal). The test plates shall be placed in an approximately vertical plane with the groove approximately horizontal (see Figure 7.6 [Detail B]).

7.8.2.3 Position 3G (Vertical). The test plates shall be placed in an approximately vertical plane with the groove approximately vertical (see Figure 7.6 [Detail C]).

7.8.2.4 Position 4G (Overhead). The test plates shall be placed in an approximately horizontal plane and the weld metal deposited from the underside (see Figure 7.6 [Detail D]).

7.8.3 Fillet Weld Test Positions. When making fillet weld macroetch soundness tests for WPS qualification, test plates shall be welded in the following positions:

7.8.3.1 Position 1F (Flat). The test plates shall be so placed that each fillet weld shall be deposited from the upper side with its axis approximately horizontal and its throat approximately vertical (see Figure 7.7 [Detail A]).

7.8.3.2 Position 2F (Horizontal). The test plates shall be so placed that each fillet weld shall be deposited on the upper side of the horizontal surface and against the vertical surface (see Figure 7.7 [Detail B]).

7.8.3.3 Position 3F (Vertical). The test plates shall be placed in approximately vertical planes, and each fillet weld shall be deposited on the vertical surfaces (see Figure 7.7 [Detail C]).

7.8.3.4 Position 4F (Overhead). The test plates shall be so placed that each fillet weld shall be deposited on the underside of the horizontal surface and against the vertical surface (see Figure 7.7 [Detail D]).

7.9 Options for WPS Qualification or Prequalification

Table 7.5 lists options available for prequalification or qualification of a WPS.

7.9.1 PJP Groove Welds. WPSs qualified for use as CJP groove welds may be used to make PJP groove welds without additional testing. The Engineer may require the Contractor to provide three macroetch test specimens to evaluate weld soundness and to verify that the required weld size is produced.

7.10 Fillet Weld WPS Qualification

7.10.1 Exemption from Groove Weld Qualification for Fillet WPS. Groove weld testing is not required to qualify WPSs for single pass fillet welds.

7.10.2 Fillet Weld Mechanical Property Tests. Except as exempted by 1.3.7, 7.10.1, or 7.11, WPSs for fillet welds shall be qualified in accordance with 7.12 using Figure 7.1.

7.10.3 Fillet Weld Soundness Test. All fillet WPSs not prequalified in accordance with 1.3.7, or 7.11 shall be subject to fillet weld soundness macroetch qualification for each weld size and position as shown in Figure 7.8. The WPS shall be qualified within the limitation of variables in Table 7.6.

(1) Two fillet weld tests may be combined in a single test weldment or assembly.

(2) The weldment shall be cut perpendicular to the direction of welding at three locations as shown in Figure 7.8. Specimens representing one face of each of the three cuts shall be polished and etched to constitute a macroetch test specimen and shall be tested in conformance with 7.19.2.

7.11 Prequalified WPS

SMAW WPSs using electrodes listed in Table 6.1 (except for E100 and E110) and steels listed in 1.2.2, operated within the current range recommended by the manufacturer, and that conform to the requirements of this code shall be considered prequalified and exempt from WPS testing.

7.11.1 Prequalified Tack Weld WPS. WPSs for tack welds that are completely remelted by subsequent SAW shall be exempt from WPS qualification testing as other-wise required by this code.

7.12 Heat Input Qualifications

This covers WPS qualification or pretesting and verification using filler metal listed in Table 6.1. The provisions of 7.12.1, 7.12.2, or 7.12.4 shall be selected for WPS qualification of joints conforming to Figure 4.4 or 4.5 (see 7.12.3 for production heat input limitations). WPSs that use groove weld details that do not conform to the details of Figure 4.4 or 4.5 shall be qualified by test as described in 7.12.4 and 7.7.5.

Heat input shall be determined using the formula:

$$\frac{\text{Heat Input}}{\text{(kJ/mm)}} = \frac{\text{Amperage} \times \text{Voltage} \times 0.06}{\text{Travel Speed (mm/minute)}}$$

$$\frac{\text{Heat Input}}{\text{(kJ/in)}} = \frac{\text{Amperage} \times \text{Voltage} \times 0.06}{\text{Travel Speed (in/minute)}}$$

The heat input for any individual weld pass in a qualification test, except the root and cap passes, shall be within ±10% of the average heat input of all the passes in the test. The amperage, voltage and travel speed for each weld pass shall be recorded. The heat input for each weld pass shall be calculated. The average heat input for the test shall be calculated using the calculated heat input values for all passes, exempting the root and cap passes, and that average shall be the WPS heat input.

7.12.1 Maximum Heat Input Qualification Test. To qualify GMAW, SAW, or FCAW WPSs for filler metals listed in Table 6.1, tests shall be conducted using Figure 7.1 (Figure 7.2 for verification).

7.12.1.1 Heat Input. The maximum heat input shall be the average heat input from the WPS qualification test as determined per 7.12.

7.12.1.2 Electrodes. The number of electrodes shall be as described in the WPS. Electrode size is not an essential variable in this method, but it shall be within the size range listed for the process in Table 7.12.

7.12.1.3 Electrical Parameters. Current type, polarity, and specified electrical electrode extension (electrode stickout) shall be the same as will be used in production. A change in electrode extension exceeding 20 mm [3/4 in] for SAW, or exceeding 6 mm [1/4 in] for FCAW or GMAW shall require requalification.

7.12.1.4 Maximum Current. The qualification test plate shall be welded with current (amperage) that meets the requirements of Clause 6 and Table 7.12. For electrode sizes not included in Table 7.12, but within the size range shown in Table 7.12 for the process, the current limit shall be interpolated from the two closest electrode sizes.

7.12.1.5 Maximum Voltage. The qualification test plate may be welded with any arc voltage as long as individual pass heat input requirements of 7.12 are met. The average arc voltage shall be calculated using the recorded voltage for each pass, exempting the root and cap pass.

7.12.1.6 Minimum Gas Flow. Shielding gas flow rate shall be the minimum to be used in production WPSs.

7.12.1.7 Travel Speed. The qualification test plate may be welded with any travel speed as long as individual pass heat input requirements of 7.12 are met.

7.12.1.8 Preheat and Interpass Temperature. The qualification test plate shall be welded with a minimum preheat and interpass temperature of 100 °C [210 °F]. Maximum preheat and interpass temperature shall be in accordance with 6.2.

7.12.1.9 Maximum Interpass Temperature. The maximum interpass temperature shall be the upper limit to be used during production welding. Production WPSs shall indicate this as the maximum interpass temperature.

7.12.2 Maximum-Minimum Heat Input Qualification Test. Testing the maximum-minimum heat input envelope for qualification of SAW, FCAW, or GMAW WPSs for filler metals listed in Table 6.1 shall be done using Figure 7.1 for qualification and Figure 7.2 for verification. With these WPS qualification methods, a maximum heat input test shall be conducted in accordance with 7.12.1, and a minimum heat input qualification test conducted in accordance with items (1) through (7) in 7.12.2.1 to establish the minimum heat input. The high and low heat input tests shall have the same electrode or electrode/flux classification, same manufacturer's brand and type for flux and cored electrodes, same nominal shielding gas composition where applicable, and same current type and polarity.

7.12.2.1 Heat Input. The WPS qualification tests shall be used to determine the maximum and minimum heat input. The maximum and minimum heat input shall be the average heat input used in making each respective qualification test plate. See 7.12 for determination of the average heat input.

(1) **Electrodes.** Number of electrodes shall be as described in the WPS. Electrode size is not an essential variable in this method, but it shall be within the size range listed for the process in Table 7.12.

(2) **Electrical Parameters.** The electrical parameters of current type, polarity, and electrode extension shall be as listed on the WPS being qualified. A change in electrode extension exceeding 20 mm [3/4 in] for SAW, or 6 mm [1/4 in] for FCAW or GMAW, shall require requalification.

(3) **Current.** The qualification test plate shall be welded with a current (amperage) that meets the requirements of Clause 6 and Table 7.12. For electrode sizes not included in Table 7.12, but within the size range for the listed process, the current limit shall be interpolated from the two closest electrode sizes.

(4) **Voltage.** The qualification test plate may be welded with any arc voltage as long as individual pass heat input requirements of 7.12 are met. The average arc voltage shall be calculated using the recorded voltage for each pass, exempting the root and cap pass.

(5) **Travel Speed.** The qualification test plate may be welded with any travel speed as long as individual pass heat input requirements of 7.12 are met.

(6) **Preheat.** The minimum preheat temperature shall be 10 °C [50 °F]. The maximum preheat temperature shall be 40 °C [100 °F].

(7) **Interpass Temperature.** The maximum interpass temperature shall not exceed 50 °C [125 °F].

7.12.3 Production Welding Limitations

7.12.3.1 Maximum Heat Input Envelope. WPSs qualified in accordance with 7.12.1 shall not exceed 100% of the heat input used in the qualification test, nor shall the heat input be less than 60% of the heat input used in the qualification test, as recorded on the PQR.

7.12.3.2 Production WPS Current, Voltage, and Travel Speed. For qualification based upon the provisions of 7.12.1, current shall be within the limits of Clause 6 and Table 7.12. The WPS current may be the same as, higher than, or lower than the value used in the maximum heat input qualification test. Voltage shall be within ±10% of the average value used in the qualification test (see 7.12.1.5), except that when welding with alloy or active fluxes the voltage shall not exceed 100% of the average voltage in the qualification test. Any travel speed may be listed. The combination of the current, voltage, and travel speed shall be such that the heat input limits of 7.12.3.1 are not exceeded.

7.12.3.3 Production Current, Voltage, and Travel Speed. Under qualification based on the provisions of 7.12.2, the production WPS current shall be within the limits of Table 7.12. The WPS current may be the same as, higher than, or lower than the values used in the maximum or minimum heat input qualification tests. WPS voltage shall be within the range bounded by 110% of the average voltage in the maximum heat input test and 90% of the average voltage in the minimum heat input test, except that when alloy or active fluxes are used, the voltage shall not exceed 100% of the average voltage in the maximum heat input test; see 7.12.2.1(4). Any WPS travel speed may be listed. The combination of the WPS current, voltage, and travel speed shall be such that the heat input limits of 7.12.3.4 are not exceeded.

7.12.3.4 Maximum-Minimum Heat Input Production Limits. The heat input of production WPSs shall be no greater than the maximum heat input as determined by the maximum heat input test (see 7.12.1), nor less than the minimum heat input determined by the minimum heat input test.

7.12.3.5 Other Welding Parameters. Production WPSs shall list a preheat in accordance with Table 6.3 or Clause 14, as applicable.

7.12.4 Production Procedure Qualification. The Production Procedure WPS qualification method shall be used to qualify the following:

(1) SAW WPSs that utilize active fluxes for other than single and two pass applications.

(2) All groove WPSs that do not use the standard joint details shown in Figures 4.4 and 4.5.

(3) WPSs that use matching strength filler metals for Grade HPS 690W [HPS 100W] steel.

At the Contractor's option, the Production Procedure WPS qualification method may be used instead of qualification in accordance with 7.12.1 or 7.12.2.

7.12.4.1 WPSs not qualified as described in 7.12.1 or 7.12.2 shall be based on the parameters of a successful qualification or verification test and the limitation of variables described in Table 7.6.

7.12.4.2 Limitations. For qualification or verification testing under the provisions of 7.12.4, the Contractor shall utilize Figure 7.1, 7.2, or 7.3 as applicable and conduct a test WPS employing production parameters. The actual values for essential variables listed in Table 7.6 shall be recorded and, together with the limitation of variables in Table 7.6, become the basis for production WPSs. Preheat and interpass temperatures for the test and production WPSs shall be within the limits set by 6.2. Production WPS variables deviating from qualified test parameters by more than what is permitted in Table 7.6 shall require requalification.

7.13 Electrogas Welding

EGW WPSs shall be qualified as specified in 7.12.4, using Figure 7.1, modified as described in 7.13.1.

7.13.1 Figure 7.1. Test plates used to qualify EGW WPSs shall conform to Figure 7.1, except the plates shall have a square butt preparation without steel backing. Figure 7.1 shall also qualify EGW T-joint welds. Test plates shall have sufficient length of weld to allow the machining and testing of eight CVN test specimens.

7.13.2 Limitations. Supplementing the variables of Table 7.6, the additional essential variables of Table 7.7 apply to EGW WPSs. Changes beyond these additional variable limits shall also require WPS requalification.

7.14 Electroslag Welding

ESW WPSs shall be qualified using Figure 7.1, modified as described in 7.14.1. Both qualification and production welds shall meet the requirements of Part F of Clause 6. The maximum thickness for each number of electrodes and joint configuration shall be tested.

7.14.1 Figure 7.1. Test plates used to qualify ESW WPSs shall conform to Figure 7.1, except the plates shall have a square butt preparation without steel backing. Figure 7.1 shall also qualify ESW T-joint welds. Test plates shall have sufficient length of weld to allow the machining and testing of eight CVN test specimens.

7.14.2 Limitations. The essential variables of Table 7.8 apply to ESW WPSs in addition to the requirements of Clause 6, Part F. Changes beyond these variable limits shall require WPS requalification.

7.15 Type of Tests and Purpose

Mechanical testing shall verify that the WPS produces the strength, ductility, and toughness required by Table 7.3 or as approved by the Engineer for the filler metal tested. Soundness tests shall meet the requirements of 7.19.1 and 7.19.2. The tests described below are used to determine the mechanical properties and the soundness of welds deposited following a given WPS. The tests are as follows:

7.15.1 Groove Welds. The following shall be tests for groove welds:

(1) All weld-metal tension tests to measure tensile strength, yield strength, and ductility.

(2) CVN test, to measure relative fracture toughness.

(3) Macroetch tests, to evaluate soundness, and to measure effective throat or weld size; also, used to determine the size and distribution of weld layers and passes.

(4) Visual examination to evaluate weld soundness.

(5) RT test to evaluate weld soundness.

(6) Reduced section tensile test, to measure tensile strength.

(7) Side-bend test, to evaluate soundness and ductility.

(8) For ESW, RT, and UT to evaluate weld soundness.

7.15.2 Fillet Welds. Tests for fillet welds shall be the following:

7.15.2.1 Mechanical Properties. The mechanical properties of fillet welds shall be measured by testing groove welds unless otherwise specified in the contract documents.

7.15.2.2 Macroetch. The fillet weld soundness macroetch test shall be used to evaluate weld soundness and to gage the size, shape, and distribution of individual weld passes.

7.16 Weld Specimens—Number, Type, and Preparation

7.16.1 Configuration. The type and number of the specimens that shall be tested to qualify a WPS are shown in Figure 7.1.

7.16.2 Mechanical Testing. Test specimens shall be removed from the test plate by thermal cutting or machining. Specimens removed by thermal cutting shall have sufficient material in the initial test blank to allow all thermal cutting HAZ material to be removed by subsequent machining. Care shall be taken not to overheat small specimens.

Each test shall include specimens described in Table 7.9.

Mechanical test specimens, except CVN test specimens, shall be prepared as follows:

(1) All-weld-metal tension test specimens, prepared for testing in conformance with Figure 7.9.

(2) Reduced section tension test specimens, prepared for testing in conformance with Figure 7.10.

(3) Side bend specimens, prepared for testing in conformance with Figure 7.11.

(4) Root and face bend specimens prepared for testing in conformance with Figure 7.12. (Used only for special applications of welder qualification.)

7.16.3 CVN Tests. The CVN test specimens shall be prepared for testing in conformance with Figure 7.13 as follows:

(1) Five specimens shall be machined from each test weld made by SMAW, SAW, FCAW, or GMAW and tested at the specified temperature.

(2) Eight specimens shall be machined from each test weld made by ESW or EGW and tested at the specified temperature.

7.17 Nondestructive Testing (NDT)

Before preparing mechanical test specimens, the qualification test plate shall be radiographed in conformance with the provisions of Clause 8, except that test plates used to qualify ESW WPSs shall also be ultrasonically inspected. Weld quality shall meet the requirements of 8.26, except that for the WPS test for M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W] steel, there shall be no discontinuities other than allowable porosity in the test weld. Portions of weld test plates marked "discard" are not subject to inspection or test.

7.18 Method of Testing Specimens

7.18.1 Reduced Section Tension Specimens. Before testing, the least width and corresponding thickness of the reduced section shall be measured in millimeters [inches]. The specimen shall be ruptured under tensile load, and the maximum load in newtons (kips) shall be determined. The cross-sectional area shall be obtained by multiplying the width by the thickness. The tensile strength shall be obtained by dividing the maximum load by the area of the cross section.

For plate thickness greater than 26 mm [1 in], full thickness specimens or multiple specimens may be used. When multiple specimens are used in lieu of full thickness specimens, each set shall represent a single tension test of the full plate thickness. When multiple specimens are used, the entire thickness shall be mechanically cut into a minimum number of approximately equal strips of a size that can be tested in available equipment. Each specimen shall meet the requirements of 7.19.3.

7.18.2 Macroetch Test. Macroetch soundness tests are required for WPS qualification testing done on test plates described in Figure 7.3 and Figure 7.8. The weld test specimens shall be prepared with a finish suitable for macroetch examination. A suitable solution shall be used for etching to give a clear definition of the welds showing the fusion line (weld-metal/base-metal interface), individual weld passes, and the HAZ.

7.18.3 Root, Face, and Side Bend Specimens. Each specimen shall be bent in a bend test jig that meets the requirements shown in Figure 7.14, 7.15, or 7.16 or is substantially in conformance with these figures, and the maximum bend radius is not exceeded. Any convenient means may be used to move the plunger member with relation to the die member.

7.18.3.1 Specimen Placement. The specimen shall be placed on the die member of the jig with the weld at mid-span. Face bend specimens shall be placed with the face of the weld directed toward the gap. Root bend and fillet weld soundness specimens shall be placed with the root of the weld directed toward the gap. Side bend specimens shall be placed with that side showing the greater discontinuity, if any, directed toward the gap.

7.18.3.2 Weld and HAZ Placement. The plunger shall force the specimen into the die until the specimen becomes U-shaped. The weld and HAZ shall be centered and completely within the bent portion of the specimen after testing.

7.18.3.3 Wraparound Jig. When using the wrap-around jig, the specimen shall be firmly clamped on one end so that there is no sliding of the specimen during the bending operation. The weld and HAZ shall be completely in the bent portion of the specimen after testing. Test specimens shall be removed from the jig when the outer roll has been moved 180° from the starting point.

7.18.4 All-Weld-Metal Tension Test. The test specimen shall be tested in conformance with ASTM A370 (AASHTO T 244), *Mechanical Testing of Steel Products* or the latest edition of AWS B4.0/B4.0M, *Standard Methods for Mechanical Testing of Welds*.

7.18.5 CVN Test. Toughness testing shall be performed as described for CVN test specimens under the heading "Charpy Impact Testing" of ASTM A370. Only full size (10 mm × 10 mm) specimens shall be used (see Figure 7.13).

7.19 Test Results Required

The requirements for the test results shall be as follows:

7.19.1 Root, Face, and Side Bend Tests. The convex surface of the bend test specimen shall be visually examined for discontinuities. For acceptance, the surface shall contain no discontinuities exceeding the following dimensions:

(1) 3 mm [1/8 in] measured in any direction on the surface

(2) 10 mm [3/8 in] for the sum of the greatest dimensions of all discontinuities exceeding 1 mm [1/32 in], but less than or equal to 3 mm [1/8 in]

(3) 6 mm [1/4 in]—the maximum corner crack, except:

(a) When the corner crack resulted from a visual slag inclusion or other fusion-type discontinuity, the 3 mm [1/8 in] maximum shall apply.

(b) Specimens with corner cracks exceeding 6 mm [1/4 in] with no evidence of slag inclusions or other fusion-type discontinuities shall be disregarded and a replacement test specimen from the original weldment shall be tested.

7.19.2 Macroetch Tests. For acceptable qualification, the macroetch test specimen, when inspected visually, shall conform to the following requirements:

7.19.2.1 General Requirements. All welds subject to the macroetch test shall conform to the following requirements:

(1) No cracks

(2) Thorough fusion between adjacent layers of weld metal and between weld metal and base metal

(3) Weld profiles conforming to design details but with none of the variations prohibited in 5.6

(4) No undercut exceeding 1 mm [1/32 in]

(5) The designated weld size (PJP groove welds)

7.19.2.2 Fillet Weld Size and Fusion

(1) Minimum fillet weld leg size shall meet the specified fillet weld size.

(2) Fillet welds shall have fusion to the root of the joint, but not necessarily beyond.

7.19.3 Reduced-Section Tension, All-Weld-Metal Tension, and CVN Tests. The mechanical properties shall conform to the values specified in Table 7.3, or as described in contract documents.

7.19.3.1 Matching Strength. For qualifying WPSs with matching strength filler metal, the mechanical properties shall conform to the values specified in Table 7.3 for the base metal listed on the WPS.

7.19.3.2 Undermatching. For qualifying WPSs with undermatching filler metal, the mechanical properties shall conform to the values specified in Table 7.3 for the base metal grade used for the qualification test (see Table 7.1).

7.19.4 Basis of Acceptance for CVN Tests. Acceptance of CVN test results shall be based on the following criteria:

(1) For SMAW, SAW, FCAW, or GMAW specimens, the highest and lowest CVN test values shall be disregarded, and the remaining three values shall be averaged. For tests to be successful, the average of the three remaining CVN test specimens energy values shall meet or exceed the minimum specified CVN test energy value. No more than one specimen may have an impact energy value less than the minimum specified and no specimen shall have a value less than 2/3 of the minimum specified value.

(2) For ESW or EGW specimens, the highest and lowest values shall be disregarded and the remaining six values shall be averaged. For tests to be successful, the average of the remaining six Charpy V-notch test values shall meet or exceed the minimum specified Charpy V-notch energy value. No more than two of the six specimens may have an impact energy value less than the minimum specified and none of the six specimens shall have a value less than 2/3 of the minimum specified value.

7.19.5 Visual Inspection. For acceptable qualification, the welded test plate when inspected visually shall conform to the requirements for visual inspection in 8.26.1, except that undercut shall not exceed 1 mm [1/32 in].

7.20 Retests

7.20.1 Tension and Bend. If any one specimen of all those tested fails to meet the test requirements, two retests for that particular type of test specimen may be performed with specimens cut from the same WPS qualification test plate or a new plate conforming to the same specification. The results of both test specimens shall meet the test requirements. For material over 38 mm [1-1/2 in] thick, failure of a specimen shall require testing of all specimens of the same type from two additional locations in the test material.

7.20.2 CVN Test. When CVN test results do not meet the requirements of 7.19.4, a retest may be made. The impact energy value of each of the required test specimens, after disregarding the highest and the lowest test values, shall equal or exceed the minimum specified CVN test energy average.

Part B
Welder, Welding Operator, and Tack Welder Qualification

7.21 General Requirements

Welders, welding operators, and tack welders using SMAW, SAW, GMAW, FCAW, ESW, and EGW welding processes shall be qualified by the tests described in Part B.

7.21.1 Purpose. The qualification tests described in Part B are specially devised tests to determine the welder's, welding operator's, or tack welder's ability to produce sound welds.

The qualification tests are not intended to be used as a guide for welding during actual construction. Construction welding shall be performed in conformance with the requirements of the WPS.

7.21.2 WPS Compliance. The welder, or welding operator, shall follow a WPS applicable to the joint details given in 7.23.1.2, 7.23.1.3, 7.23.1.4, or 7.23.1.5, whichever is applicable.

7.21.3 Base Metal. The base metal used shall be an AASHTO approved steel as described in 1.2.2 or the WPS (see 7.24.1.1).

7.21.4 Period of Effectiveness. The welder's, welding operator's, or tack welder's qualification as described in this code shall be considered as remaining in effect indefinitely unless (1) the welder, welding operator, or tack welder is not engaged in a given process of welding for which the welder, welding operator, or tack welder is qualified for a period exceeding six months, or (2) there is some specific reason to question a welder's, welding operator's, or tack welder's ability. In case of (1), the requalification test need be made only in the 10 mm [3/8 in] thickness. If the welder fails a requalification test given in the case of (1), then full requalification testing shall be required, as if for a new welder.

7.21.5 Weld Cleaning

7.21.5.1 Root and Fill Pass Cleaning. Cleaning between weld passes shall be limited to hand chipping and hand-wire brushing, or power wire brushing. The use of power tools to perform chipping, grinding, or cutting on root or intermediate weld passes shall be prohibited. Power chippers or grinders shall not be used during the weld test. Upon weld test completion and after visual inspection, the weld may be made flush by power tools as necessary in order to facilitate testing (see 7.26).

7.21.5.2 Cleaning Position. Weld cleaning shall be done with the test weld in the same position as the welding position being qualified.

7.21.6 Responsibility

7.21.6.1 Contractor. Each Contractor shall conduct tests or verify that the welders, welding operators, and tack welders are qualified as required by this code.

7.21.7 Records. Records of the test results shall be kept by the manufacturer or Contractor and shall be available to those authorized to examine them.

7.21.8 Previous Code Editions. Welders, welding operators, and tack welders qualified to previous editions of this code shall be considered qualified to this code. Qualification test records shall not be required to be converted to metric (SI) Units of measure if the tests were performed using U.S. Customary Units and vice versa.

7.22 Production Welding Positions Qualified

7.22.1 Welder Qualification. Position requirements for welder qualification shall be in accordance with Table 7.10.

7.22.2 Welding Operator Qualification. Welding operators shall qualify for each position of production welding.

7.22.3 Tack Welder Qualification. A tack welder who passes the fillet weld break test shall be eligible to tack weld all types of groove joints and fillets using the process and the welding position tested.

7.23 Qualification Tests Required

7.23.1 Welder Qualification. The welder qualification test for manual and semiautomatic welding shall conform to the following requirements:

(1) Groove weld qualification tests for plate of unlimited thickness in conformance with 7.23.1.2

(2) Groove weld qualification tests for plate of limited thickness in conformance with 7.23.1.3

(3) Fillet weld qualification tests (for fillet welding only) in conformance with 7.23.1.4

(4) Plug weld qualification tests (for plug welds only) in conformance with 7.23.1.5

7.23.1.1 WPS Qualification. A welder who makes a CJP groove weld WPS qualification test that meets the requirements of this code is thereby qualified to weld by that process in the positions qualified by the test position. The maximum thickness qualified is based on test plate thickness as listed in Table 7.11. The limitations of 7.21.5, do not apply to a welder qualified by welding a satisfactory WPS qualification test plate. The welder shall also be qualified for fillet welding and slot welding of plate and shapes for the process and position tested.

7.23.1.2 Groove Weld Qualification Test for Plate of Unlimited Thickness. The joint details shall be as follows: 25 mm [1 in] plate, single-V-groove, 45° included angle, 6 mm [1/4 in] root opening with backing (see Figure 7.17). For horizontal position qualification, the joint detail may, at the Contractor's option, be as follows: single-bevel-groove, 45° groove angle, 6 mm [1/4 in] root opening with backing (see Figure 7.18). If RT is used, backing shall be 6 mm [1/4 in] min. to 10 mm [3/8 in] by 75 mm [3 in]. For mechanical testing, backing may be 6 mm [1/4 in] to 10 mm [3/8 in] by 25 mm [1 in] min. The minimum length of the welded groove shall be 125 mm [5 in].

7.23.1.3 Groove Weld Qualification Test for Plate of Limited Thickness. The groove detail shall be as follows: 10 mm [3/8 in] plate, single-V-groove, 45° included angle 6 mm [1/4 in] root opening with backing (see Figure 7.19). For horizontal position qualification, the joint detail may, at the Contractor's option, be as follows: single-bevel-groove 45° groove angle, 6 mm [1/4 in] root opening with backing (see Figure 7.20). Backing shall be 6 mm [1/4 in] min. to 10 mm [3/8 in] max by 75 mm [3 in] min., if RT is used. For mechanical testing after the backing is removed, it shall be 6 mm [1/4 in] min. to 10 mm [3/8 in] max. by 25 mm [1 in]. The minimum length of welding groove shall be 180 mm [7 in].

7.23.1.4 Qualification Tests for Fillet Welds Only. Requirements for fillet weld qualification only, on plate and rolled structural shapes, shall be as follows:

(1) For fillet welds between parts having a dihedral angle (Ψ) of less than 60°, the welder shall weld a groove weld test plate as required by 7.23.1.2 or 7.23.1.3. This qualification shall also be valid for joints having a dihedral angle (Ψ) of 60° and greater.

(2) For joints having a dihedral angle (Ψ) of 60° or greater, but not exceeding 135°, the welder shall weld a test plate according to Option 1 or Option 2, depending on the Contractor's choice, as follows:

(a) *Option 1.* Weld a T-test plate in conformance with Figure 7.21.

(b) *Option 2.* Weld a soundness test plate in conformance with Figure 7.22.

7.23.1.5 Plug Weld Qualification Tests for Plug Welds Only. The joint shall consist of a 20 mm [3/4 in] diameter hole in a 10 mm [3/8 in] plate with a 10 mm [3/8 in] minimum thickness backing plate (see Figure 7.23).

7.23.2 Welding Operator Qualification

7.23.2.1 Joint Requirements for Processes Other Than ESW or EGW. The welding operator qualification test for other than plug welds and ESW or EGW welding shall have a joint detail as follows: 25 mm [1 in] plate, single-V-groove, 20° included groove angle, 16 mm [5/8 in] root opening with backing. Backing shall be 10 mm [3/8 in] to 12 mm [1/2 in] by

75 mm [3 in] min. if RT is used without removal of backing. If backing is removed, at least 40 mm [1-1/2 in] width of backing shall be used. The minimum length of welding groove shall be 400 mm [15 in] (see Figure 7.24).

This test will qualify the welding operator for groove and fillet welding in materials of unlimited thickness for the process and position tested.

Alternatively, the welding operator may be qualified by RT of the initial 400 mm [15 in] of a production groove weld. The material thickness range qualified shall be that shown in Table 7.11.

7.23.2.2 Joint Requirements for ESW or EGW. The qualification test for an ESW or EGW welding operator shall consist of welding a joint of the maximum thickness of material to be used in construction, but the thickness of the material of the test weld need not exceed 38 mm [1-1/2 in] (see Figure 7.25). If a 38 mm [1-1/2 in] thick test weld is made, no test need be made for lesser thicknesses. This test shall qualify the welding operator for groove and fillet welds in material of unlimited thickness for this process and test position.

7.23.2.3 WPS Qualification. A welding operator may also be qualified by welding a satisfactory WPS qualification test plate, as described in 7.12, 7.13, and 7.14, that meets the requirements of 7.19. That welding operator shall be qualified to weld plate with the process and in the test position used for WPS qualification. The limitations of 7.21.5 do not apply to a welding operator qualified by welding a satisfactory WPS qualification test plate. That welding operator shall also be qualified for slot welding for the process and position tested. The thickness range qualified shall be as described in Table 7.11.

7.23.2.4 Qualification Tests for Fillet Welds Only. Requirements for fillet weld qualification only, on plate and rolled structural shapes, shall conform to the following requirements:

(1) For fillet welds between parts having a dihedral angle (Ψ) of 60° or less, the welding operator shall weld a groove weld test plate as required by 7.23.2. This qualification shall also be valid for joints having a dihedral angle (Ψ) of 60° and greater.

(2) For joints having a dihedral angle (Ψ) greater than 60°, but not exceeding 135°, the welding operator shall weld a test plate in conformance with Option 1 or Option 2, depending on the Contractor's choice, as follows:

(a) *Option 1.* Weld a T-test plate in conformance with Figure 7.26.

(b) *Option 2.* Weld a soundness test plate in conformance with Figure 7.27.

7.23.3 Tack Welding Qualification. The following options shall qualify an individual to perform tack welding for the process used in the test, for any thickness:

(1) For tack welding qualification only, the individual shall make a tack weld no greater than 6 mm (1/4 in.) in size and 50 mm (2 in.) long on the fillet weld specimen shown in Figure 7.28, for each position in which tack welds are to be made.

(2) A welder qualified by Options (1), (2), or (3) in 7.23.1 or by the test described in 7.23.1.1 shall also be qualified to tack weld. Tack welders shall be qualified to weld in the positions permitted by 7.22.

7.24 Limitations of Variables

7.24.1 Common Requirements for Welders, Welding Operators, and Tack Welders. The following requirements shall apply to welder, welding operator, and tack welder qualification (see 7.24.2 for specific limitations for welders, 7.24.3 for welding operators, and 7.24.4 for tack welders).

7.24.1.1 Base Metal. Qualification established with any one of the steels allowed by this code shall be considered as qualification to weld or tack weld any of the other steels with the following exception:

Qualification to weld or tack weld steel with a minimum yield strength of 620 MPa [90 ksi] or greater shall be established with steel meeting the same specification as steel for the project.

7.24.1.2 Process. A welder, welding operator, or tack welder shall be qualified for each process used.

7.24.1.3 Approved Electrode and Shielding Medium. A welder, welding operator, or tack welder qualified with an approved electrode and shielding medium combination shall be considered qualified to weld or tack weld with any other approved electrode and shielding medium combination for the process used in the qualification test.

7.24.2 Welder Qualification Variables Only. These requirements shall only apply to welder qualification.

7.24.2.1 SMAW Restrictions. A welder qualified for SMAW using EXX18 or EXX18-X electrodes shall be qualified to weld with all SMAW electrodes allowed under this code, except welders required to use an electrode classification of E100XX-X or higher to join metals with a minimum specified yield strength of 620 MPa [90 ksi] or greater shall be tested using E10018-X or E11018-X electrodes as necessary to match the yield strength of the base metal to be used in the work.

7.24.2.2 Position. A change in the position of welding to one for which the welder is not already qualified shall require requalification (see Table 7.10). When the plate is in the vertical position, change in the direction of welding shall require requalification.

7.24.2.3 Backing. Omission of backing material (if the welder was qualified using backing) in CJP welds welded from one side shall require requalification.

7.24.3 Welding Operator Qualification Variables Only. The following requirements shall only apply to welding operator qualification.

7.24.3.1 ESW/EGW. An ESW or EGW welding operator qualified with an approved electrode and shielding medium combination shall be considered qualified to weld with any other approved electrode and shielding medium combination for the process used in the qualification test.

7.24.3.2 Processes Other than ESW/EGW. For other than ESW or EGW welding, a welding operator qualified to weld with multiple electrodes shall be qualified to weld with a single electrode, but not vice versa.

7.24.3.3 Position. A change in the position in which plate is welded shall require requalification.

7.24.3.4 Machine Welder Qualification. Welders qualified for SAW shall be considered qualified for single-electrode mechanized welding in the same process(es) subject to the limitations of 7.24, provided the welding operators receive training and demonstrate their ability to make satisfactory production welds.

7.24.4 Tack Welder Qualification Variables Only. The following requirements shall apply only to tack welder qualification.

7.24.4.1 SMAW Restrictions. A tack welder qualified for SMAW using EXX18 electrodes shall be qualified to tack weld with all SMAW electrodes allowed under this code. Tack welding shall be performed using E7018 electrodes, unless the contract documents require tack welding with electrodes classified E10018-X, E11018-X, or E12018-X. Tack welders shall be qualified for the particular electrode used.

7.24.4.2 Position. A change in the position in which tack welding is done shall require requalification.

7.25 Test Specimens: Number, Type, and Preparation

7.25.1 Welder Requirements. The type and number of test specimens that shall be tested to qualify a welder by mechanical testing are shown in Table 7.11, together with the range of thickness that is qualified for use in construction by the thickness of the test plate used in making the qualification. RT of the test weld may be used, at the Contractor's option in lieu of mechanical testing. RT shall not be an option for GMAW-S. Weld backing shall not be removed from welds subject to RT.

7.25.2 Welding Operator Requirements. For mechanical testing, guided bend test specimens shall be prepared by cutting the test plate as shown in Figure 7.24, 7.25, or 7.27, whichever is applicable, to form specimens approximately rectangular in cross section. The specimens shall be prepared for testing in conformance with Figure 7.11 or 7.12, as applicable. For ESW. either RT or UT may be substituted for mechanical testing.

7.25.3 Tack Welder Requirements. One test specimen shall be welded as shown in Figure 7.28 with the entire welded assembly as the test specimen.

7.26 Method of Testing Specimens

7.26.1 Radiographic Testing. Except for joints welded by GMAW-S, RT of welder and welding operator qualification test plates may be made in lieu of guided bend tests described in Part B of this section (see 6.13.4 for clarification of short-circuiting transfer).

7.26.1.1 Weld Reinforcement. If RT is used in lieu of the prescribed bend test, the weld reinforcement shall be finished either flush or with slight reinforcement remaining so that there are no lines or surface irregularities that may obscure discontinuities in the radiograph. Weld backing shall not be removed from welds subject to RT.

7.26.1.2 RT Procedure for Welder Qualification. The RT procedure and technique shall be in conformance with the requirements of Clause 8, Part B. Exclude 30 mm [1-1/4 in] at each end of the weld from evaluation in the plate test.

7.26.1.3 RT Procedure for Welding Operator Qualification. The RT procedure and technique shall be in conformance with the requirements of Clause 8, Part B. At each end of the length of the test plate, 75 mm [3 in] shall be excluded from evaluation.

7.26.2 Guided Bend Test for Welder Qualification. Guided bend test specimens shall be prepared by cutting the test plate as shown in Figures 7.17, 7.18, 7.19, or 7.20, whichever is applicable, to form specimens approximately rectangular in cross section. The specimens shall be prepared for testing in conformance with Figures 7.11 or 7.12, as applicable.

7.26.2.1 Root, Face, and Side Bend Specimens. See 7.18.3 for specimen requirements.

7.26.3 Fillet Weld Break and Macroetch Test Requirements

7.26.3.1 Welder Qualification. The fillet weld break and macroetch test specimens shall be cut from the test joint, as shown in Figure 7.21. The end of the macroetch test specimen shall be smooth for etching. The entire length of the fillet weld shall be examined visually and then the 150 mm [6 in] specimen shall be loaded in such a way that the root of the weld is in tension. The load shall be steadily increased or repeated until the specimen fractures or bends flat upon itself.

7.26.3.2 Welding Operator Qualification. The fillet weld break and macroetch test specimens shall be cut from the test joint as shown in Figure 7.26. The end of the macroetch test specimen shall be smooth for etching. The entire length of the fillet weld shall be examined visually and then a 150 mm [6 in] long specimen shall be loaded in such a way that the root of the weld is in tension. The load shall be steadily increased or repeated until the specimen fractures or bends flat upon itself.

7.26.3.3 Tack Welder Qualification. A force shall be applied to the specimen as shown in Figure 7.29, until rupture occurs. The force may be applied by any convenient means. The surface of the weld and of the fracture shall be examined visually for defects.

7.26.3.4 Macroetch Test. The test specimens shall be prepared with a finish suitable for macroetch examination. A suitable solution shall be used to give a clear definition of the weld.

7.27 Test Results Required

7.27.1 Visual Inspection of Welder and Welding Operator Test Plates. For acceptable qualification, the welded test plates, when inspected visually, shall conform to the requirements for visual inspection in 8.26.1, except that undercut shall not exceed 1 mm [1/32 in]. Weld reinforcement shall not exceed 5 mm [3/16 in].

7.27.2 RT. For acceptable qualification, the weld, as revealed by the radiograph, shall conform to the requirements of 8.26.2, except that 8.26.2.2 shall not apply.

7.27.3 Root or Side Bend Tests. The convex surface of the bend test specimen shall be visually examined for surface discontinuities. For acceptance, the surface shall contain no discontinuities exceeding the following dimensions:

(1) 3 mm [1/8 in] measured in any direction on the surface

(2) 10 mm [3/8 in] for the sum of the greatest dimensions of all discontinuities exceeding 1 mm [1/32 in], but less than or equal to 3 mm [1/8 in]

(3) 6 mm [1/4 in]—the maximum corner crack, except when that corner crack resulted from visible slag inclusion or other fusion-type discontinuities, then the 3 mm [1/8 in] maximum shall apply

Specimens with corner cracks exceeding 6 mm [1/4 in] with no evidence of slag inclusions or other fusion-type discontinuities may be disregarded, and a replacement test specimen from the original weldment shall be tested.

7.27.4 Fillet Weld Break Test (Welder and Welding Operator)

7.27.4.1 Visual Examination. To pass the visual examination, the fillet weld shall present a reasonably uniform appearance and shall be free of overlap, cracks, and excessive undercut. There shall be no porosity visible on the surface of the weld.

7.27.4.2 Fracture Surface. The specimen shall pass the test if it bends flat upon itself. If the fillet weld fractures, the fractured surface shall show complete fusion into the root of the joint and shall exhibit no inclusion or porosity larger than 2 mm [1/16 in] in the greatest dimension. The sum of the greatest dimensions of all inclusions and porosity shall not exceed 10 mm [3/8 in] in the 150 mm [6 in] specimen.

7.27.5 Fillet Weld Break Test (Tack Welder)

7.27.5.1 Visual Examination. The tack weld shall present a uniform appearance and shall be free of overlap, cracks, and excessive undercut exceeding 1 mm [1/32 in]. There shall be no porosity visible on the surface of the tack weld.

7.27.5.2 Fracture Surface. The fracture surface of the tack weld shall show fusion to the root but not necessarily beyond and shall exhibit no incomplete fusion to the base metal nor any inclusion or porosity larger than 2 mm [1/16 in] in greatest dimension.

7.27.6 Macroetch Test

7.27.6.1 Fillet Welds. Macroetch test specimens, when inspected visually, shall conform to the following requirements:

(1) No cracks

(2) Thorough fusion between adjacent layers of weld metals and between weld metal and base metal

(3) Weld profiles conforming to intended detail, but with none of the variations prohibited in 5.6

(4) No undercut exceeding 1 mm [1/32 in]

(5) Fusion to the root of the joint but not necessarily beyond

(6) Leg sizes equal to or greater than the specified leg size

7.27.6.2 Plug Welds. Macroetch test specimens for plug welds, when inspected visually, shall conform to the following requirements:

(1) No cracks

(2) Thorough fusion to backing plate and to sides of the hole

(3) No visible slag in excess of 6 mm [1/4 in] total accumulated length

7.28 Retests

7.28.1 Welder and Welding Operator. If a welder or welding operator fails to meet the requirements of one or more test welds, a retest may be allowed under the following conditions:

7.28.1.1 Immediate Retest. An immediate retest may be made consisting of two test welds of each type and position that the welder or welding operator failed. All retest specimens shall meet all the specified requirements.

7.28.1.2 Retest After Further Training or Practice. A retest may be made provided there is evidence that the welder or welding operator has had further training or practice. A complete retest of the types and positions failed shall be made. The retesting of the welder or welding operator shall be a complete retest for the failed weld test coupon, including all specimens required in Table 7.11.

7.28.2 Tack Welder. In case of failure to pass the fillet weld break test, the tack welder may make one retest without additional training.

Table 7.1
Base Metal Options for WPS Qualification Test Plates
[AASHTO M 270M/M 270 (ASTM A709/A709M) Grades (see 7.4 and C-7.4)]

Filler Metal Strength to be listed on WPS MPa [ksi]	Base Metal Grade to be Listed on WPS			
	Gr. 250 [36]	**Gr. 345, 345S, 345W, HPS° 345W [50, 50S, 50W, HPS° 50W]**	**Gr. HPS° 485W [HPS° 70W]**	**Gr. HPS° 690W [HPS° 100W]**
415 [60]	Gr. 250 [36], or 345 [50], or 345W [50W], or HPS° 345W [HPS 50W]	Gr. 250 [36], or 345 [50], or 345W [50W], or HPS° 345W [HPS 50W]	Gr. 250 [36], or 345 [50], or 345W [50W], or HPS° 345W [HPS 50W]	Gr. 250 [36], or 345 [50], or 345W [50W], or HPS° 345W [HPS 50W]
485 [70] or 550 [80]	—	Gr. 345 [50] 345W [50W] HPS° 345W [HPS 50W]	Gr. 345 [50] 345W [50W] HPS° 345W [HPS 50W]	Gr. 345 [50] 345W [50W] HPS° 345W [HPS 50W]
620 [90]	—	—	Gr. HPS° 485W [HPS° 70W]	Gr. HPS° 485W [HPS° 70W]
690 [100] or 760 [110]	—	—	—	Gr. HPS° 690W [HPS° 100W]

Table 7.2 (see 7.4 and C-7.4)
AASHTO and ASTM Equivalent Base Metal Grades

AASHTO M 270M/M 270 (A709/A709M) Grade	ASTM equivalent
Gr. 250 [36]	A36/A36M
Gr. 345 [50]	A572/A572M Gr. 345 [50]
Gr. 345W [50W]	A588/A588M, Gr. A or B

Table 7.3
Test Requirements for WPSs Qualified in Conformance with 7.12[a,b,c]

Qualified Base Metal AASHTO (ASTM) Designation	Reduced Section Minimum Tensile Strength, MPa [ksi]	All-Weld-Metal Minimum Yield Strength, MPa [ksi]	All-Weld-Metal Minimum Tensile Strength, MPa [ksi]	All-Weld-Metal Minimum Elongation in 50 mm [2 in], %	Minimum CVN, J [ft·lb] AASHTO Temperature Zones[d]	
					I and II	III[e]
M 270M/M 270 (A709/A709M) Gr. 250 [36]	400 [58]	300 [45]	415 [60]	22	27 @ –20 °C [20 @ 0 °F]	27 @ –30 °C [20 @ –20 °F]
M 270M/M 270 (A709/A709M) Gr. 345 [50] Type 1, 2, 3; Gr. 345S [50S]	450 [65]	345 [50]	450 [65]	22	27 @ –20 °C [20 @ 0 °F]	27 @ –30 °C [20 @ –20 °F]
M 270M/M 270 (A 709/A709M) Gr. 345W [50W] (up to 100 mm [4 in] thick), Gr. HPS 345W [HPS 50W]	485 [70]	345 [50]	485 [70]	22	27 @ –20 °C [20 @ 0 °F]	27 @ –30 °C [20 @ –20 °F]
M 270M/M 270 (A709/A709M) Gr. HPS 485W [HPS 70W]	585 [85]	485 [70]	620 [90]	17	34 @ –25 °C [25 @ –10 °F]	34 @ –30 °C [25 @ –20 °F]
M 270M/M 270 (A709/A709M) Gr. HPS 690W [HPS 100W] over 60 mm [2-1/2 in] thick	690 [100]	620 [90]	690 [100]	16	27 @ –40 °C [20 @ –40 °F]	As Approved by Engineer
M 270M/M 270 (A709/A709M) Gr. HPS 690W [HPS 100W] 60 mm [2-1/2 in] thick or less	760 [110]	690 [100]	760 [110]	20	27 @ –40 °C [20 @ –40 °F]	As Approved by Engineer

a. Procedures prequalified in accordance with accordance with 7.11 or 12.7.1 are exempt from testing.
b. When welds are to be stress-relieved, the stress-relieved weld shall meet the minimum mechanical properties and impact properties specified in the contract.
c. The Engineer may accept the results of test that vary from the limits established by this table based upon the following rules:
  1) The yield strength of the weld metal may be up to 70 MPa [10 ksi] less than the minimum specified yield strength of the matching weld metal when stress in the weld is compression normal to the effective area of the weld.
  2) Ductility and toughness shall be as specified, except when otherwise approved for specific projects or applications.
  3) Acceptance of modified mechanical properties by one State does not obligate other States to accept the same modifications.
d. See AASHTO *LRFD Bridge Design Specification* for definitions of AASHTO temperature zones.
e. ESW not permitted for Zone III. EGW CVN requirements as approved by the Engineer.

Table 7.4
WPS Qualification Requirements for Consumables (see 7.5.1)

Consumables	Process					
	FCAW	SAW	GMAW	SMAW	ESW	EGW
Each AWS filler metal classification	X	X	X	X	X	X
Each manufacturer's brand and type of cored electrode	X	X	X		X	X
Each manufacturer's brand and type of flux		X			X	
Each shielding gas or combination of shielding gases[a]	X		X			X

[a] Differences of 25% or less in the minor element of the mixture proportions shall not require separate tests.

Note: An "X" indicates applicability for the process; a shaded block indicates nonapplicability.

Table 7.5
WPS Qualification or Prequalification Options (see 7.9)

Joint Detail(s)	Process(es)	Qualification Options per Subclause(s)
Groove detail conforming to Figure 4.4 or 4.5	SMAW	Prequalified if listed in 7.11 or 12.7.1, as applicable
		7.12.4 if not prequalified
	FCAW, SAW, GMAW	7.12.1, 7.12.2, or 7.12.4
Any groove detail not conforming to Figure 4.4 or 4.5 (including all ESW and EGW)	all	7.12.4
Fillet Welds	all	7.10

Table 7.6
PQR Essential Variable Changes for WPSs Qualified per 7.12.4

Essential Variable Changes to PQR Requiring Requalification	Process				
	Shielded Metal Arc Welding (SMAW)	Submerged Arc Welding (SAW)	Gas Metal Arc Welding (GMAW)	Flux Cored Arc Welding (FCAW)	Electrogas Welding (EGW)
Filler Metal					
1) Addition or deletion of supplemental powdered or granular filler metal or cut wire		X			
2) Increase or decrease in the amount of supplemental powdered or granular filler metal or wire		X			
3) If the alloy content of the weld metal is largely dependent on supplemental powdered filler metal, any WPS change that results in a weld deposit with the important alloying elements not meeting the WPS chemical composition requirements		X			
4) A change in the ratio of supplemental powdered, granular filler metal, or cut wire to electrode		X			
Electrode					
5) Increase or decrease in electrode diameter by more than one standard size	X	X	X	X	X
6) Change in number of electrodes	X	X	X	X	X
7) A change in the amperage by:	To a value not recommended by the electrode manufacturer	>10% increase or decrease	>10% increase or decrease	>10% increase or decrease	>20% increase or decrease
8) A change in type of current (AC or DC) or polarity	X	X	X	X	X
9) A change in mode transfer (see Annex M)			X		
10) A change in the voltage by:		>7% increase or decrease	>7% increase or decrease	>7% increase or decrease	

(Continued)

Table 7.6 (Continued)
PQR Essential Variable Changes for WPSs Qualified per 7.12.4

	Process				
Essential Variable Changes to PQR Requiring Requalification	Shielded Metal Arc Welding (SMAW)	Submerged Arc Welding (SAW)	Gas Metal Arc Welding (GMAW)	Flux Cored Arc Welding (FCAW)	Electrogas Welding (EGW)
11) For WPSs using alloy or active fluxes, any increase in the maximum voltage		X			
12) A change in the travel speed by:		>15% increase or decrease	>10% increase or decrease	>10% increase or decrease	>20% increase or decreaseb
13) An increase or decrease of more than 20% in heat input[b]	X	X	X	X	X
Multiple Electrode SAW					
14) A change >10%, or 3 mm [1/8 in], whichever is greater, in the longitudinal spacing of the arcs		X			
15) A change of >10%, or 2 mm [1/16 in], whichever is greater, in the lateral spacing of the arcs		X			
16) An increase or decrease of more than 10° in the angular orientation of any parallel electrode		X			
17) For machine or automatic SAW; an increase or decrease of more than 3° in the direction of travel		X			
18) For machine or automatic SAW, an increase or decrease of more than 5° normal to the direction of travel		X			
General					
19) For the PQR groove area, an increase or decrease >25% in the number of passes[a, c]	X	X	X	X	X
Qualification with Figure 7.1 or Figure 7.2					
20) A change from a U-groove to a V-groove (but not vice versa)	X	X	X	X	
21) A change in the type of groove to a square groove and vice versa	X	X	X	X	

(Continued)

Table 7.6 (Continued)
PQR Essential Variable Changes for WPSs Qualified per 7.12.4

	Process				
Essential Variable Changes to PQR Requiring Requalification	Shielded Metal Arc Welding (SMAW)	Submerged Arc Welding (SAW)	Gas Metal Arc Welding (GMAW)	Flux Cored Arc Welding (FCAW)	Electrogas Welding (EGW)
22) A change exceeding the tolerances of 4.12, 4.13, or 5.3.4 in the shape of any type of groove involving: (a) A decrease in the groove angle (b) A decrease in the root opening (c) An increase in the root face that will not be subsequently removed by backgouging	X	X	X	X	
23) The omission, but not inclusion, of backing or backgouging	X	X	X	X	
24) Addition or deletion of PWHT	X	X	X	X	X
25) For M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W], increase in plate thickness greater than 12 mm [1/2 in] or decrease of 25 mm [1 in] or more	X	X	X	X	
Qualification with Figure 7.8					
26) A change in nominal fillet weld size (as listed in Figure 7.8)	X	X	X	X	
27) For the same nominal fillet weld size, an increase or decrease >25% in the number of passes	X	X	X	X	
28) A change in the dihedral angle by more than 10° (increase or decrease)[d]	X	X	X	X	

[a] If the production weld groove area differs from that of the PQR groove area, the number of passes may be changed in proportion to the area without requiring WPS requalification.
[b] For M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W], allowable heat input increase or decrease shall be limited to 10%.
[c] For M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W], any change in the number of groove weld passes requires requalification, except proportional changes to accommodate a change in weld cross-sectional area. For fillet welds in these steels, any change in the number of passes requires a fillet weld T-test per Figure 7.8 to be performed.
[d] See 4.8.4 for limits on fillet weld dihedral angles.

Notes:
1. An "X" indicates applicability for the process; a shaded block indicates nonapplicability.
2. The production welding preheat or interpass temperature may be less than the PQR preheat or interpass temperature provided that the provisions of Table 6.3 or Annex F are met.
3. Solid wire electrodes conforming to the same AWS filler metal classification may be interchanged without requalification (see Table 7.4).
4. These limitations apply for travel speed changes that are not an automatic function of arc length or deposition rate, and are not applicable when necessary to compensate for variation in joint opening as approved by the Engineer.
5. See 7.5.1 for additional WPS qualification requirements.

Table 7.7
Additional PQR Essential Variable Changes Requiring WPS Requalification for EGW (see 7.13.2)

Essential Variable Changes to PQR Requiring Requalification	Requalification by WPS Test	Requalification by Radiographic or Ultrasonic Test[a]
Molding Shoes (fixed or movable)		
1) A change from metallic to nonmetallic or vice versa	X	
2) A change from fusing to nonfusing or vice versa	X	
3) A reduction in any cross-sectional dimension or area of a solid nonfusing shoe >25%	X	
4) A change in design from nonfusing solid to water cooled or vice versa	X	
Filler Metal Oscillation		
5) A change in oscillation traverse speed >4 mm/s [10 in/min]		X
6) A change in oscillation traverse dwell time >2 s (except as necessary to compensate for joint operating variations—as approved by the Engineer)		X
7) A change in oscillation traverse length that affects the proximity of filler metal to the molding shoes by more than 3 mm [1/8 in]		X
Filler Metal Supplements		
8) A change in consumable guide metal core cross-sectional area >30%	X	
9) A change in the flux system, i.e., cored, magnetic electrode, external, etc.	X	
10) A change in flux composition including consumable guide coating	X	
11) An increase or decrease in flux burden exceeding 30%	X	
Process Characteristics		
12) A change to a combination with any other welding process	X	
13) A change from single pass to multi-pass and vice versa	X	
14) A change from constant current to constant voltage and vice versa		X
Wire Feed Speed		
15) An increase or decrease in the wire feed speed >40%	X	
Groove Type		
16) A change in groove design, reducing cross-sectional area (for nonsquare grooves)	X	
17) A change in WPS joint thickness, outside limits of 0.5T –1.1T (T = qualification thickness)	X	
18) An increase or decrease >6 mm [1/4 in] in square groove root opening	X	

[a] Testing shall be performed in conformance with Clause 8, Part E or F, as applicable.

Note: An "X" indicates applicability for the requalification method; a shaded block indicates nonapplicability.

Table 7.8
PQR Essential Variable Changes Requiring WPS Requalification for ESW (see 1.3.4 and 7.14.2)

(1) Increase or decrease in electrode diameter.

(2) Change in number of electrodes.

(3) A change in the configuration of the consumable guide. A change to the guide area proportional to a change in plate thickness shall not require requalification.

(4) A change in flux composition.

(5) A change in consumable guide electrical insulator composition. A change to vitreous aluminosilicate fiber does not require requalification.

(6) A decrease in consumable guide electrical insulator spacing.

(7) A change in consumable guide electrical insulator size or method of attachment.

(8) A change in cooling shoe design altering its operating characteristics.

(9) Addition or deletion of PWHT.

(10) A change to WPS joint thickness greater than that of the qualification weld.

(11) A change in type of current (AC or DC) or polarity.

Table 7.9
Required Number of Test Specimens—WPS Qualification (see 7.16.2)

Test Plate Figure	All Weld Metal Tension Test	Reduced Section Tension Test	Side Bend Test	CVN Test	Groove Weld Macroetch Test	Fillet Weld Macroetch Test
7.1	1	2	4	5[a]	(Note b)	—
7.2	1	—	2	5	—	—
7.3	—	2	4	—	2	—
7.8	—	—	—	—	—	3

[a] Eight CVN tests shall be required for ESW and EGW.
[b] When required by the Engineer.

Table 7.10
Welder Qualification—Type and Position Limitations (see 7.22)

Qualification Test		Type of Weld and Position of Welding Qualified	
		Plate	
Weld	Positions	Groove	Fillet
Plate-groove	1G	F	F, H
	2G	F, H	F, H
	3G	F, H, V	F, H, V
	4G	F, OH	F, H, OH
	3G and 4G	All	All
Plate-fillet[a]	1F		F
	2F		F, H
	3F		F, H, V
	4F		F, H, OH
	3F and 4F		All
Plate-Plug[b]	1F	F	
	3F	V	
	4F	OH	

[a] Not applicable for fillet welds between parts having a dihedral angle (Ψ) of 60° or less (see 7.23.1.4).
[b] Applicable only to qualification of plug welds (see 7.23.1.5).

Table 7.11
Number and Type of Specimens and Range of Thickness Qualified—Welder and Welding Operator Qualification (see 7.25.1)

1. Test on Plate

Type of Weld	Thickness of Test Plate (T) as Welded, mm [in]	Visual Inspection	Number of Specimens					Plate Thickness Qualified, mm [in]
			Bend Tests[e]			T-Joint Break	Macro-Etch Test	
			Face	Root	Side			
Groove[f]	10 [3/8]	Yes	1	1	—	—	—	20 [3/4] max.[c, g]
Groove	10 < T < 25 [3/8 < T < 1]	Yes	—	—	2	—	—	2T[c, d] max.
Groove	25 [1] or over	Yes	—	—	2	—	—	Unlimited[c]
Fillet Option No. 1[a]	12 [1/2]	Yes	—	—	—	1	1	Unlimited
Fillet Option No. 2[b]	10 [3/8]	Yes	—	2	—	—	—	Unlimited
Plug	10 [3/8]	Yes	—	—	—	—	2	Unlimited

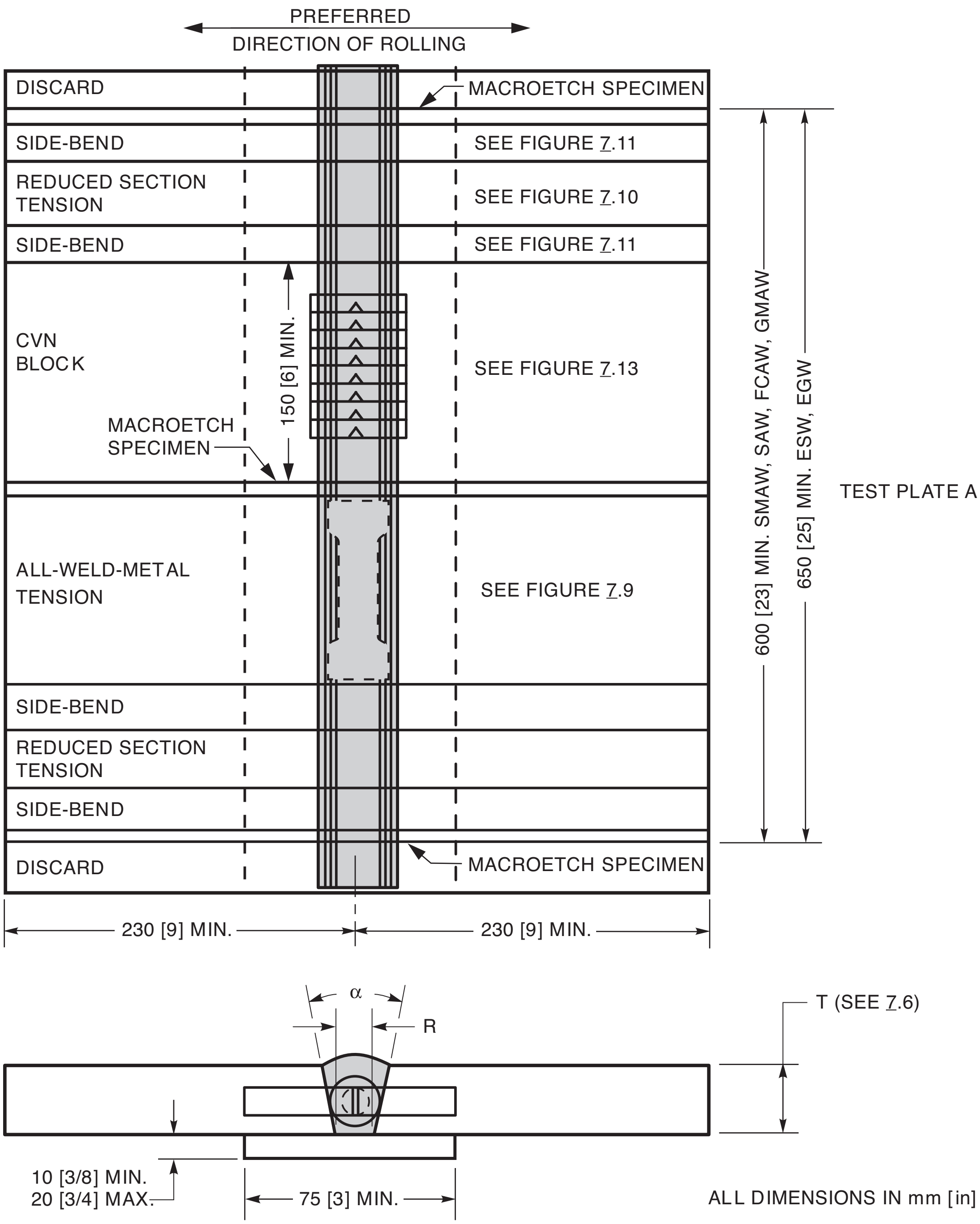
2. Tests on Electroslag and Electrogas Welding

Plate Thickness Tested, mm [in]	Test Specimens Required			Plate Thickness Qualified, mm [in]
	Number of Sample Welds	Visual Inspection	Side Bend (see Figure 7.23)	
38 [1-1/2] max.	1	Yes	2	Unlimited for 38 [1-1/2] Max. tested for <38 [1-1/2]

[a] See Figure 7.21.
[b] See Figure 7.22.
[c] Also qualifies for fillet welding on material of unlimited thickness.
[d] T max. for welding operator qualification.
[e] RT of test plate may be made in lieu of the bend test. This shall not be allowed for GMAW-S.
[f] Not applicable for welding operator qualification.
[g] See Figures 7.19 and 7.20.

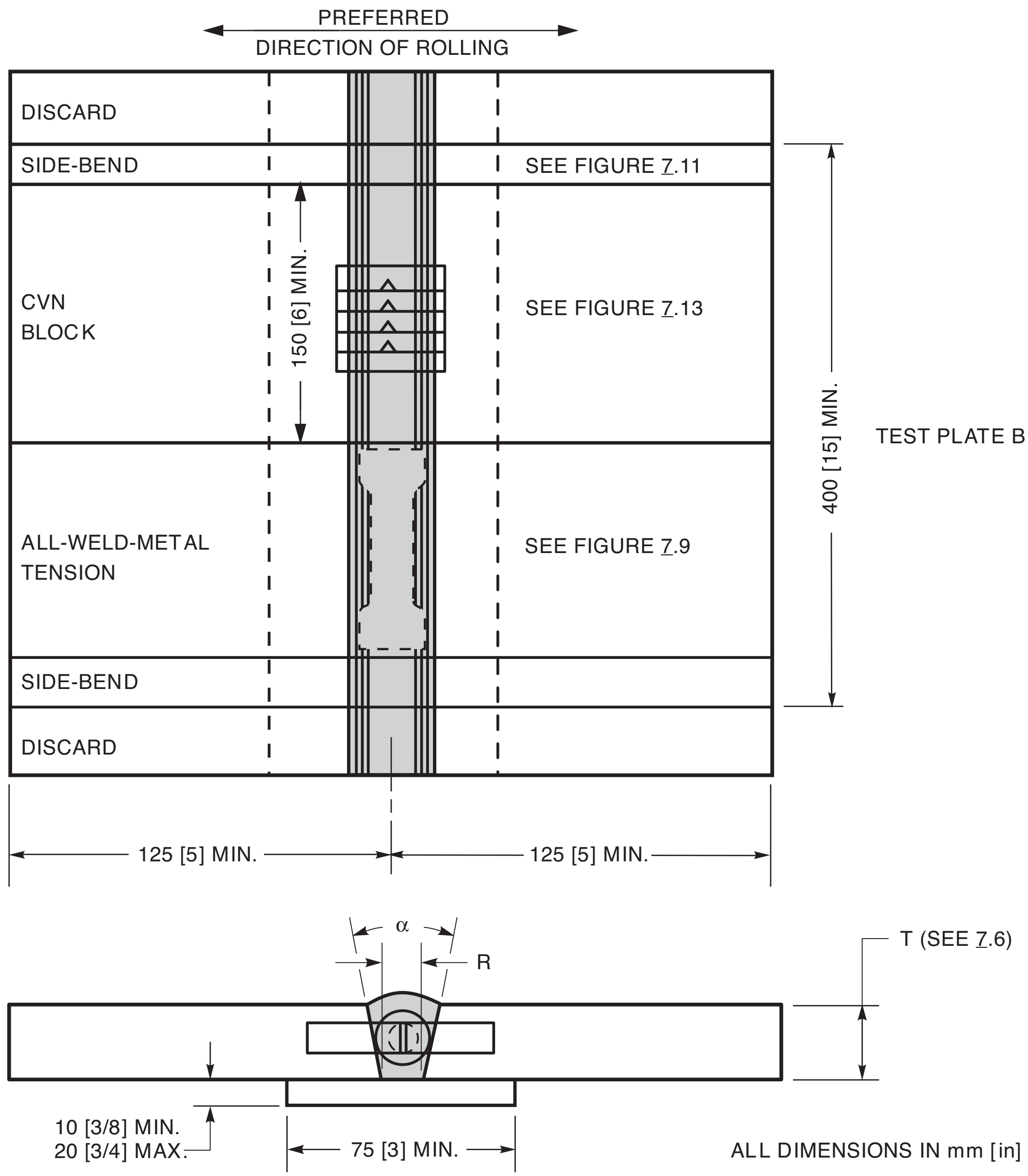
Table 7.12
Amperage Limits for Heat Input Welding Procedure Qualification

Process	Electrode Size mm [in]	Minimum Amperage	Maximum Amperage
SAW Solid Electrode	1.6 [1/16]	200	500
	2.0 [5/64]	235	600
	2.4 [3/32]	250	700
	3.2 [1/8]	300	800
	4.0 [5/32]	400	1000
	4.8 [3/16]	500	1200
	5.6 [7/32]	600	1300
SAW Cored Electrode	2.4 [3/32]	200	650
	3.2 [1/8]	250	700
	4.0 [5/32]	400	900
	4.8 [3/16]	500	1100
FCAW-G	1.1 [0.045]	175	335
	1.3 [0.052]	180	405
	1.6 [1/16]	200	480
	2.0 [5/64]	250	550
	2.4 [3/32]	335	650
FCAW-S	1.6 [1/16]	175	315
	1.7 [0.068]	190	355
	1.8 [0.072]	190	400
	2.0 [5/64]	195	435
	2.4 [3/32]	200	525
	2.8 [7/64]	310	625
GMAW Solid Electrode	0.9 [0.035]	175	250
	1.0 [0.040]	200	320
	1.1 [0.045]	225	430
	1.3 [0.052]	275	430
	1.6 [1/16]	290	430
GMAW Metal Cored Electrode	1.1 [0.045]	190	385
	1.3 [0.052]	190	455
	1.6 [1/16]	230	510
	2.0 [5/64]	275	550
	2.4 [3/32]	325	600



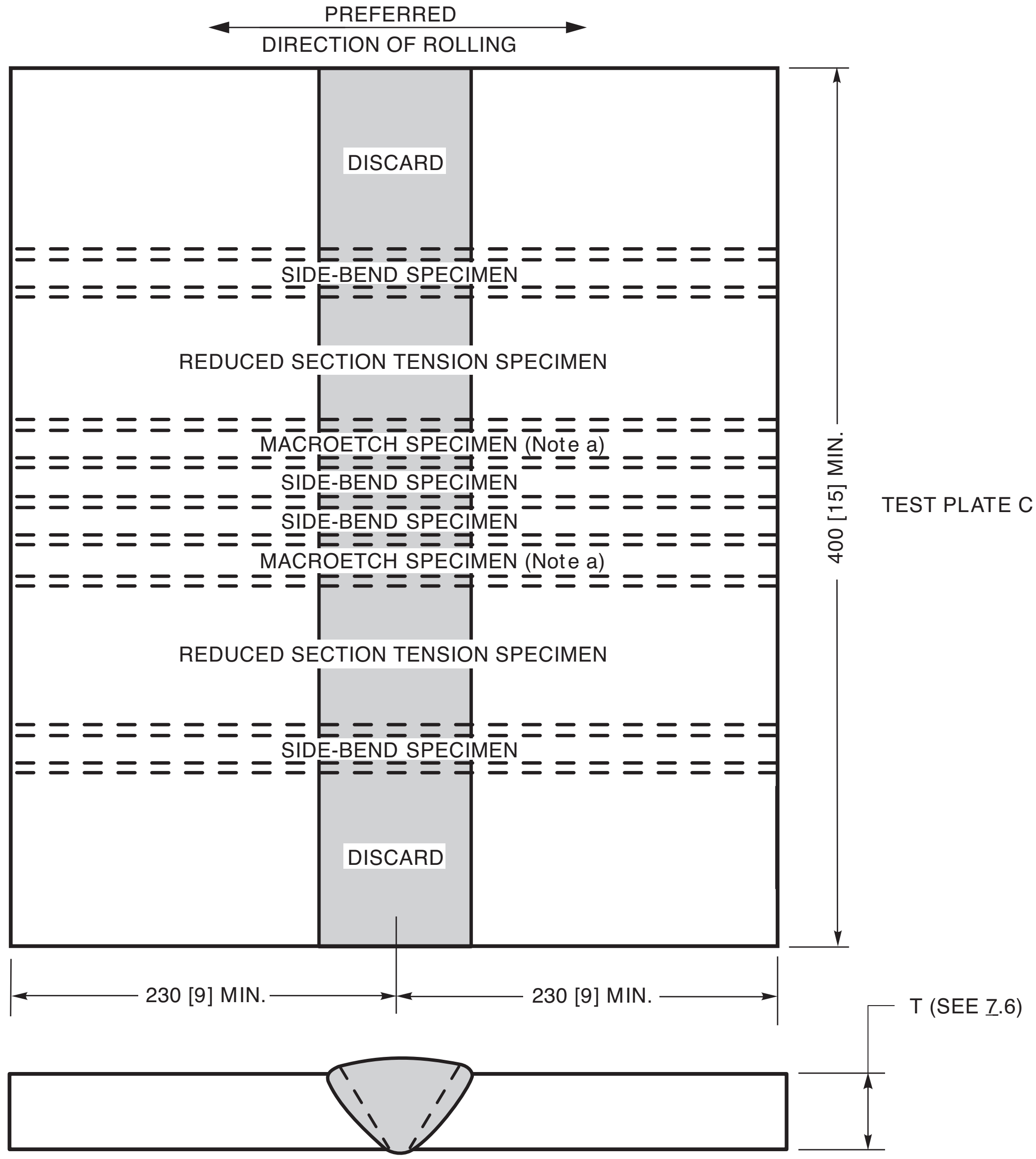
Notes:
1. Welding and machining shall be witnessed by a state representative or an independent third party acceptable to the state.
2. Test specimens and the PQR showing all welding parameters used for the test shall be available to the Engineer. Test specimens need only be retained for examination by the original approving authority.
3. The joint detail to be used shall be either a B-U2a, B-U2-S, B-U2a-GF, B-U4a, or B-U4a-GF detail, depending on the welding process used and the position of the welding, except that the B-U2a-GF and B-U4a-GF with the 5 mm [3/16 in] root opening and 30° included angle shall not be used.

Figure 7.1—WPS Qualification or Pretest—Test Plate A (see 7.7.1)



Notes:
1. Test specimens need only be retained for examination by the original approving authority. Welding and machining shall be witnessed by a state representative or an independent third party acceptable to the state.
2. Test specimens and the PQR showing all welding parameters used for the test shall be available to the Engineer. Test specimens need only be retained for examination by the original approving authority.
3. Testing shall be done by an approved testing laboratory. Such testing need not be witnessed by another agency.
4. The joint detail to be used shall be either a B-U2a, B-U2-S, B-U2a-GF, B-U4a, or B-U4a-GF detail, depending on the welding process used and the position of the welding, except that the B-U2a-GF and B-U4a-GF with the 5 mm [3/16 in] root opening and 30° included angle shall not be used.

Figure 7.2—WPS Verification—Test Plate B (see 7.7.3)



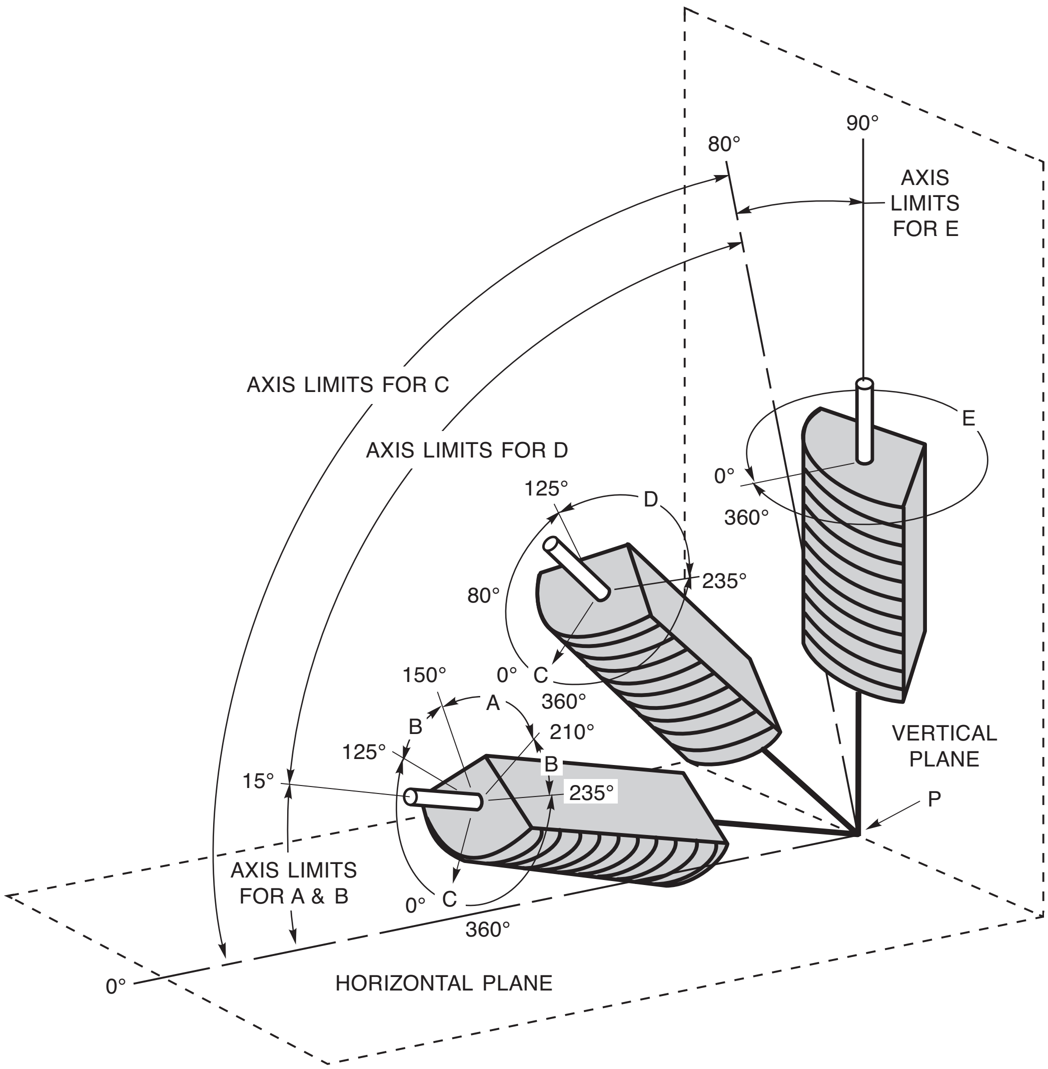
[a] Macroetch specimens 10 mm [3/8 in] thick and "T" wide shall be polished and etched for macroscopic examination by the Engineer.

Notes:
1. Welding and machining shall be witnessed by a state representative or an independent third party acceptable to the state.
2. Test specimens and the PQR showing all welding parameters used for the test shall be available to the Engineer. Test specimens need only be retained for examination by the original approving authority.
3. Testing shall be done by an approved testing laboratory. Such testing need not be witnessed by another agency.

Figure 7.3—Weld Soundness Test Plate for Details Not Conforming to Figure 4.4 or 4.5—Test Plate C (see 7.7.5)

Tabulation of Positions of Fillet Welds

Position	Diagram Reference	Inclination of Axis	Rotation of Face
Flat	A	0° to 15°	150° to 210°
Horizontal	B	0° to 15°	125° to 150° 210° to 235°
Overhead	C	0° to 80°	0° to 125° 235° to 360°
Vertical	D	15° to 80°	125° to 235°
	E	80° to 90°	0° to 360°

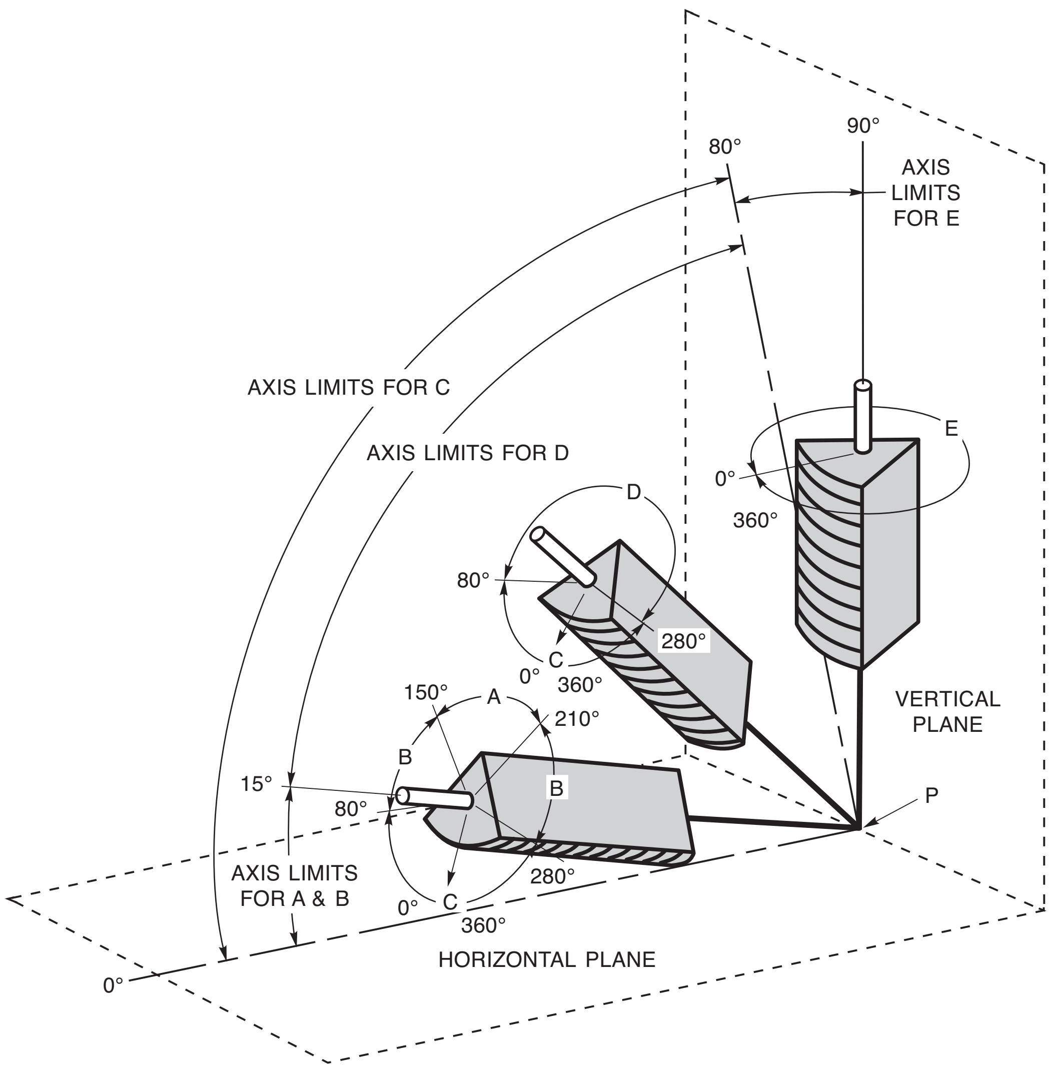


Notes:
1. The horizontal reference plane shall always be taken to lie below the weld under consideration.
2. The inclination of axis shall be measured from the horizontal reference plane toward the vertical reference plane.
3. The angle of rotation of the face shall be determined by a line perpendicular to the theoretical face of the weld that passes through the axis of the weld. The reference position (0°) of rotation of the face invariably points in the direction opposite to that in which the axis angle increases. When looking at point P, the angle of rotation of the face of the weld shall be measured in a clockwise direction from the reference position (0°).

Figure 7.4—Positions of Fillet Welds (see 7.8.1)

Tabulation of Positions of Fillet Welds

Position	Diagram Reference	Inclination of Axis	Rotation of Face
Flat	A	0° to 15°	150° to 210°
Horizontal	B	0° to 15°	80° to 150° 210° to 280°
Overhead	C	0° to 80°	0° to 80° 280° to 360°
Vertical	D	15° to 80°	80° to 280°
	E	80° to 90°	0° to 360°



Notes:
1. The horizontal reference plane shall always be taken to lie below the weld under consideration.
2. The inclination of axis shall be measured from the horizontal reference plane toward the vertical reference plane.
3. The angle of rotation of the face shall be determined by a line perpendicular to the theoretical face of the weld that passes through the axis of the weld. The reference position (0°) of rotation of the face invariably points in the direction opposite to that in which the axis angle increases. When looking at point P, the angle of rotation of the face of the weld shall be measured in a clockwise direction from the reference position (0°).

Figure 7.5—Positions of Groove Welds (see 7.8.1)

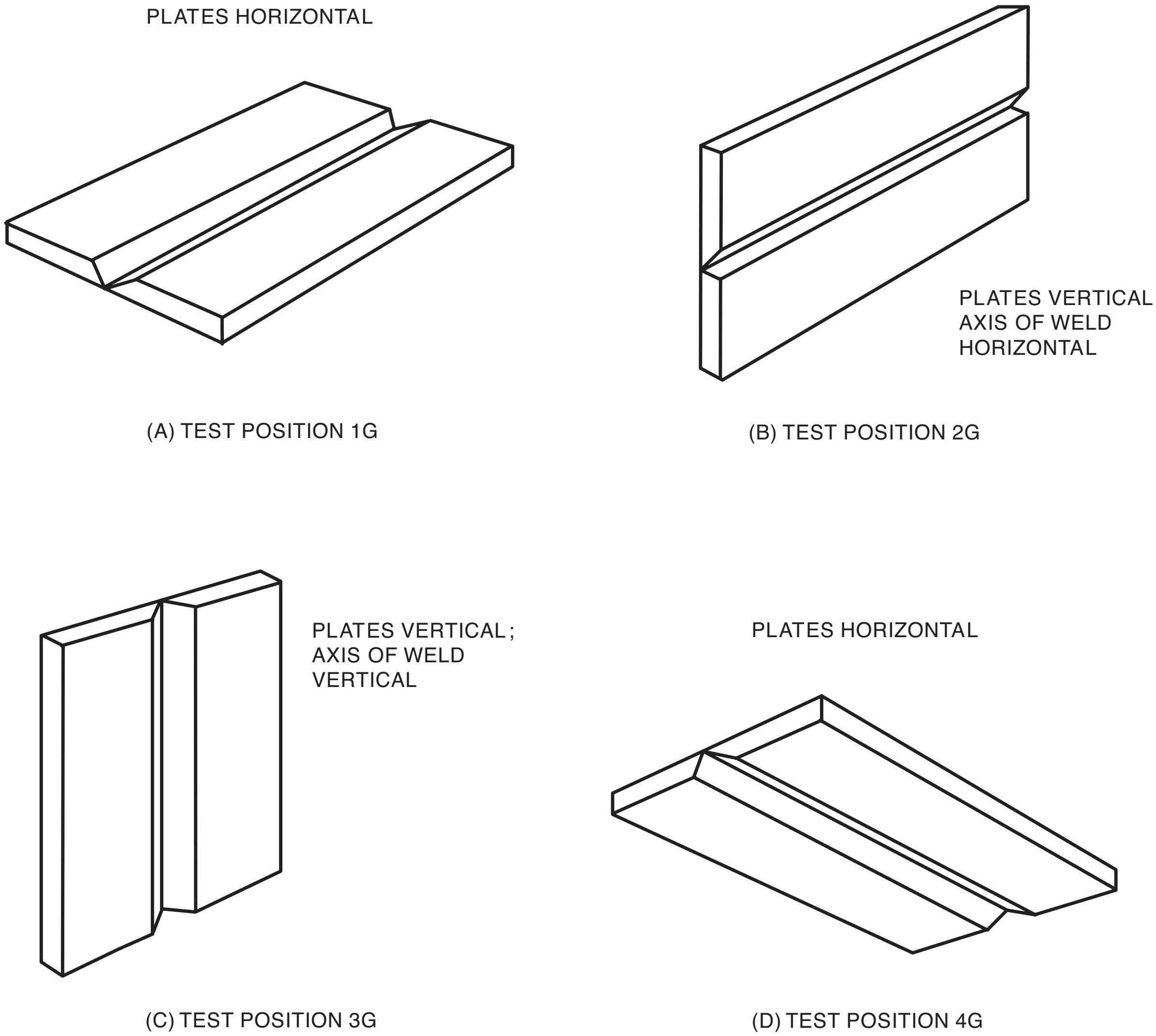


Figure 7.6—Positions of Test Plates for Groove Welds (see 7.8.2)

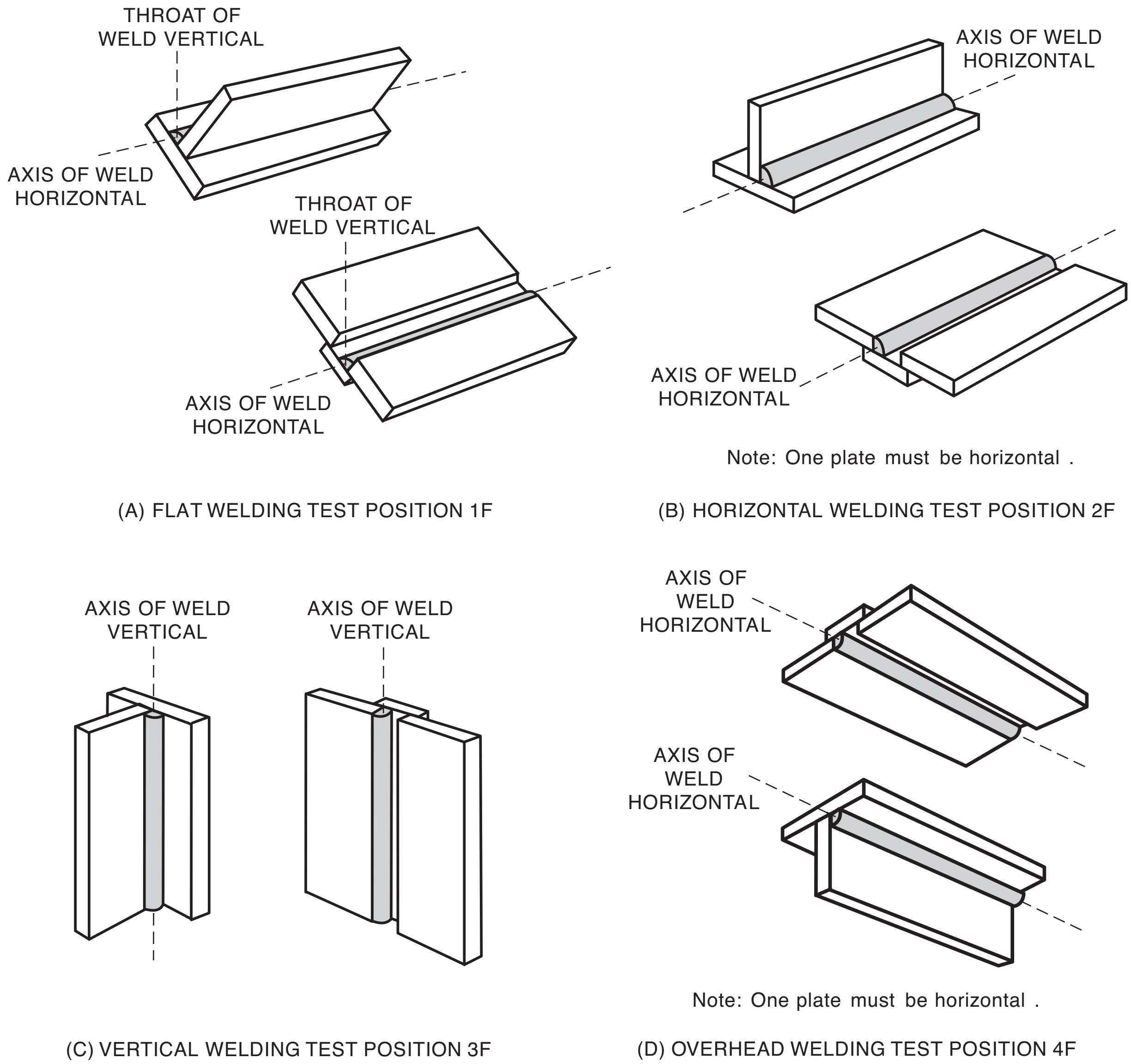
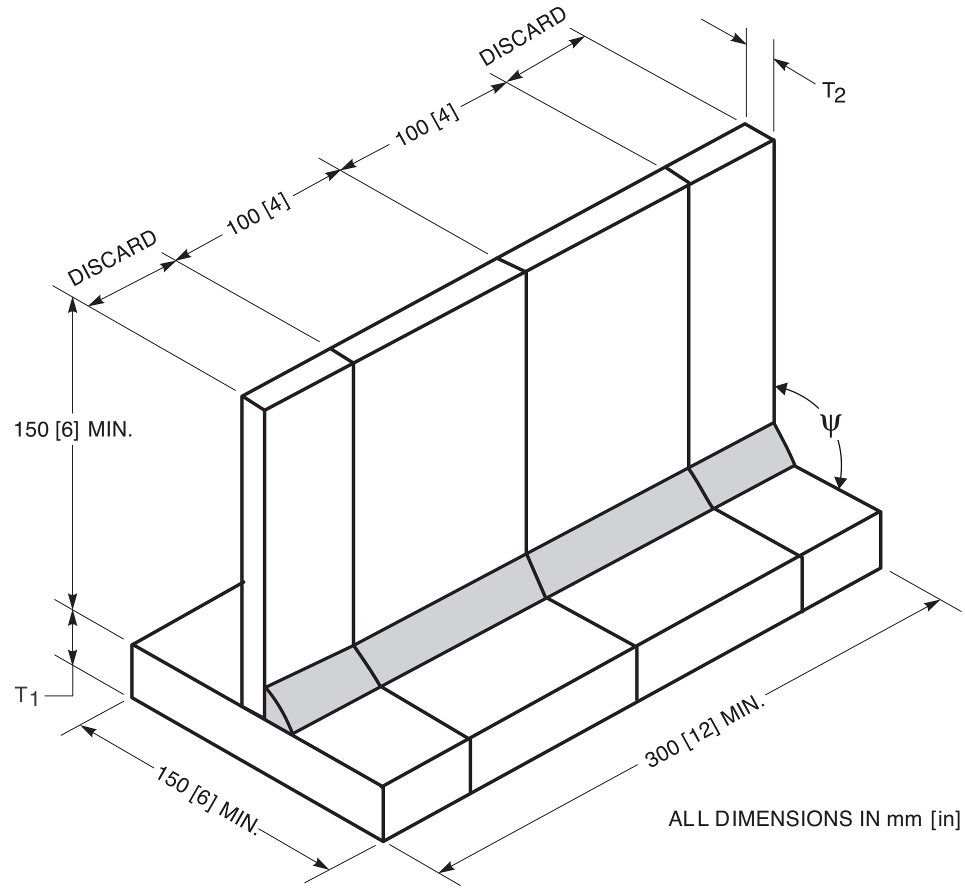
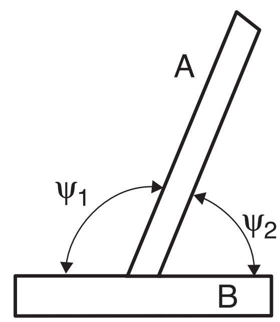


Figure 7.7—Positions of Test Plates for Fillet Welds (see 7.8.3)



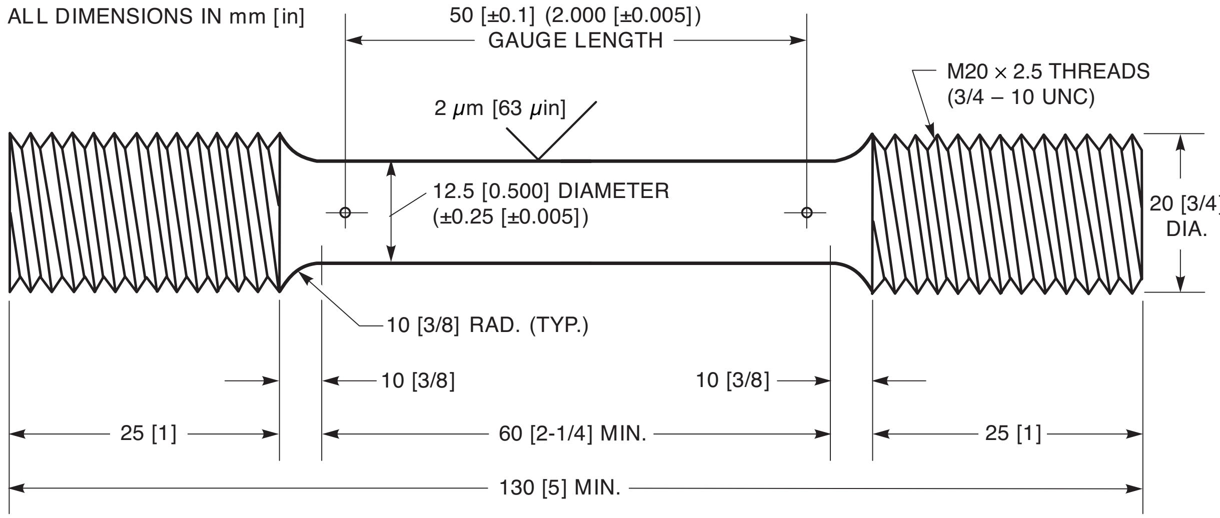
WELD SIZE	T_1 MIN.	T_2 MIN.
5 [3/16]	12 [1/2]	12 [1/2]
6 [1/4]	20 [3/4]	12 [1/2]
8 [5/16]	25 [1]	12 [1/2]
10 [3/8]	25 [1]	12 [1/2]
12 [1/2]	25 [1]	12 [1/2]
16 [5/8]	25 [1]	16 [5/8]
20 [3/4]	25 [1]	20 [3/4]
>20 [>3/4]	25 [1]	25 [1]



MACROETCH TEST SPECIMEN

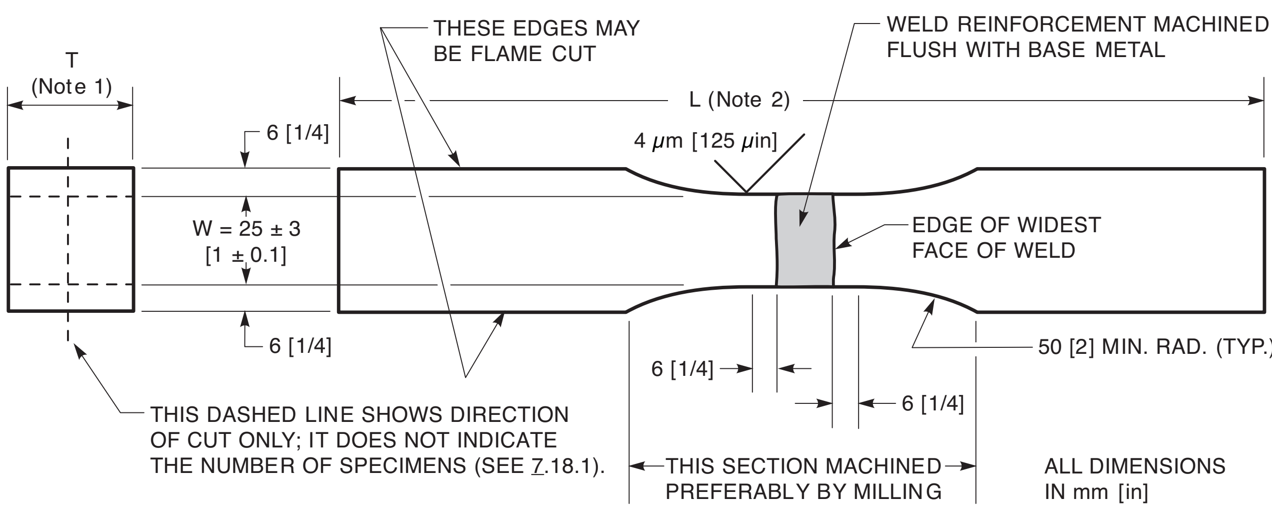
Notes:
1. Where the maximum plate thickness used in production is less than the value shown in the table, the maximum thickness of the production pieces may be substituted for T_1 and T_2.
2. At the contractor's option, two tests may be combined into one specimen (For example: tests for $\Psi = 70°$ and $\Psi = 110°$ may be combined.)
3. Root opening shall not exceed 2 mm [1/16 in]. Plate may be beveled as needed to maintain this requirement.
4. Ψ is the dihedral angle to be qualified.

Figure 7.8—Fillet Weld Soundness Test (Macroetch) for WPS Qualification—Test Plate D (see 7.10)



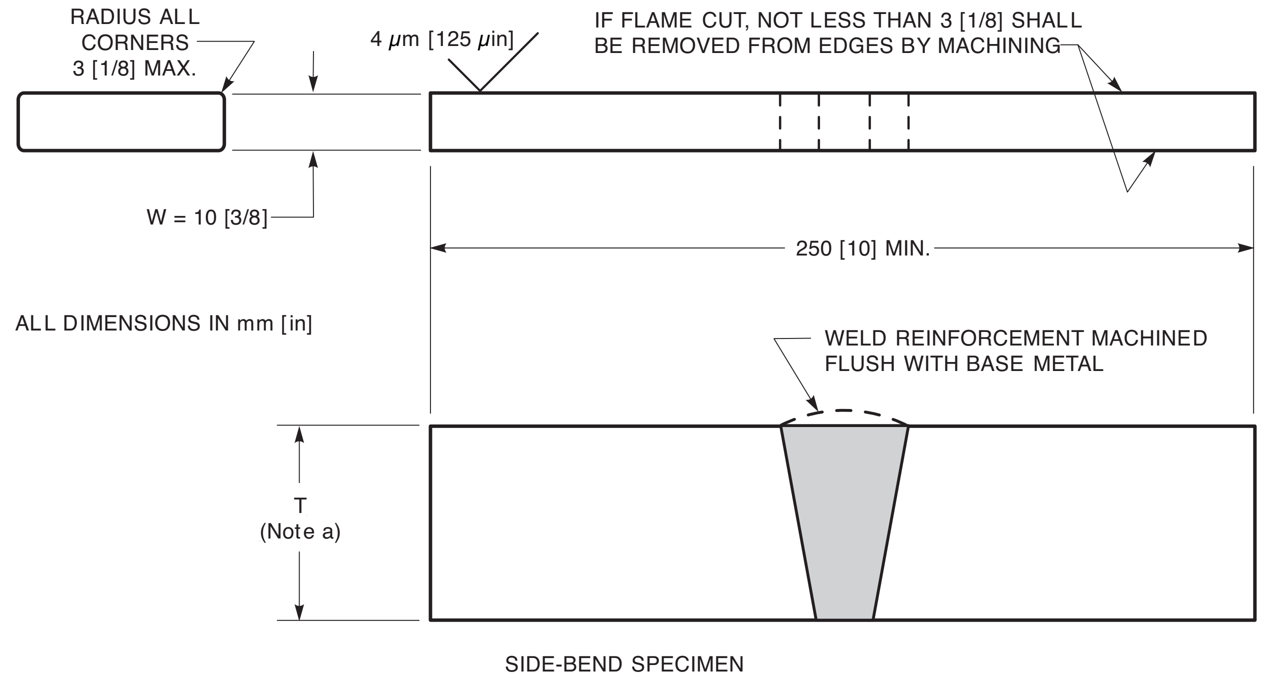
Notes:
1. The reduced section may have a gradual taper from the ends toward the center with the ends not more than 0.1 mm [0.005 in] larger in diameter than the center.
2. The all-weld metal tension specimen shall be taken from the center of the thickness of the weld, and from the center of the width of the weld at this location.

Figure 7.9—Standard Round All-Weld-Metal Tension Specimen (see 7.16.2)



Notes:
1. T depends on the thickness of test plate shown in Figure 7.1 or 7.3; see 7.6.
2. L shall be the overall length of the test specimen. The length shall be sufficient to facilitate gripping in the testing apparatus. When practicable, the specimen should extend into the grips a distance greater than or equal to 2/3 the length of the grip.
3. Weld reinforcement and steel backing, if any, shall be removed flush with the surface of the specimen.

Figure 7.10—Reduced Section Tension Specimen (see 7.16.2)



[a] T depends on the thickness of test plate shown in Figures 7.1, 7.2, and 7.3; see 7.6. If T > 40 mm [1-1/2 in], see AWS B4.0 for guidance on cutting the specimen into strips between 20 mm and 40 mm [3/4 in to 1-1/2 in] wide.

Figure 7.11—Side-Bend Specimen (see 7.16.2)

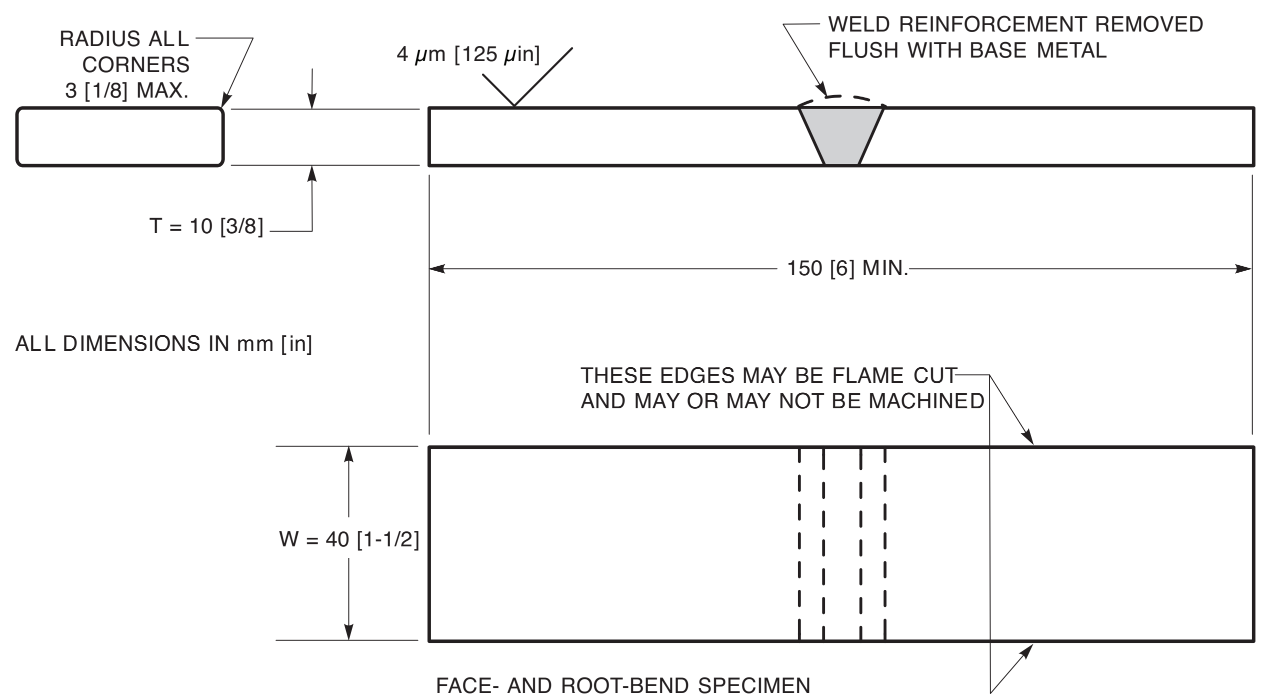
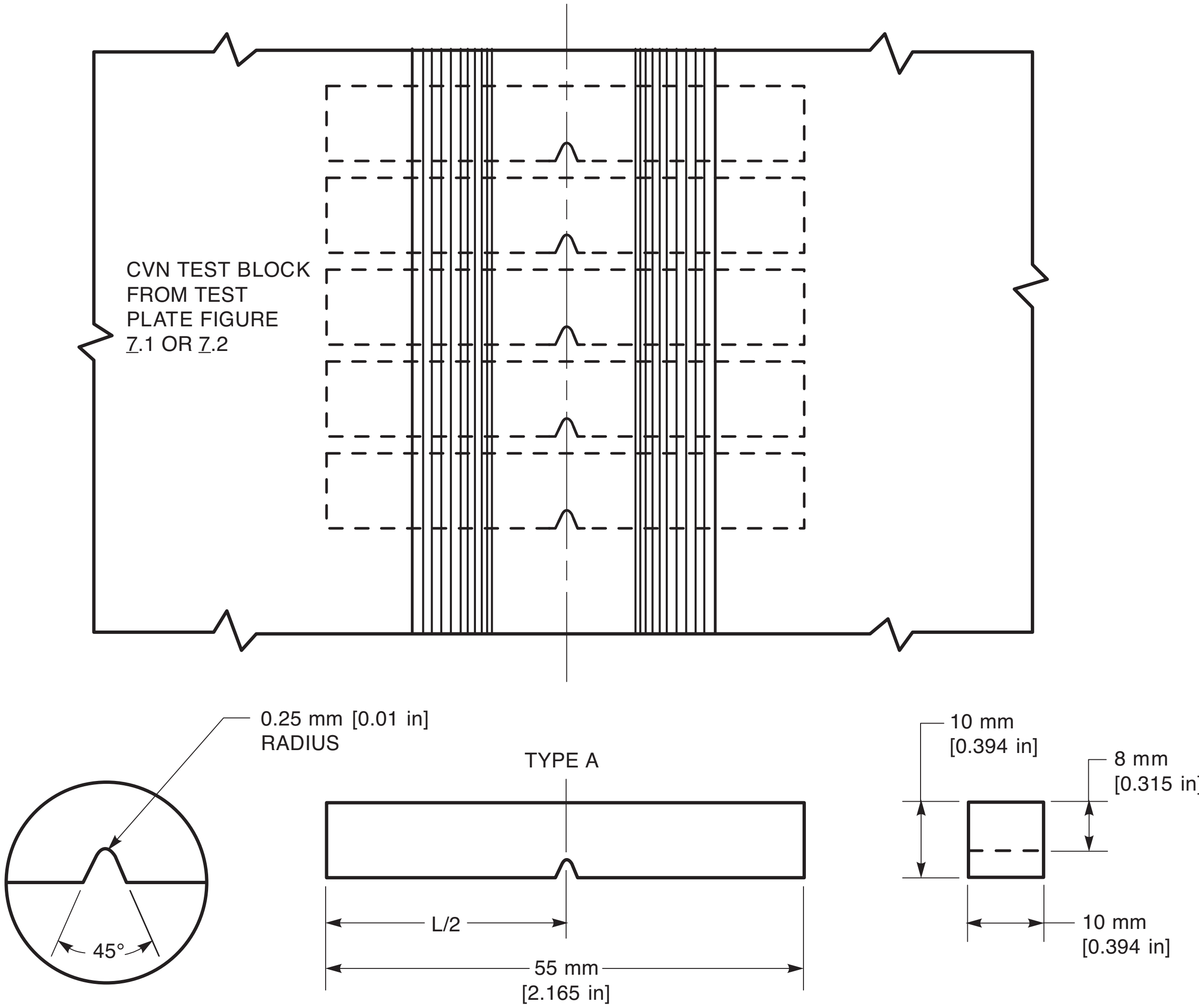


Figure 7.12—Face- and Root-Bend Specimen (see 7.16.2)

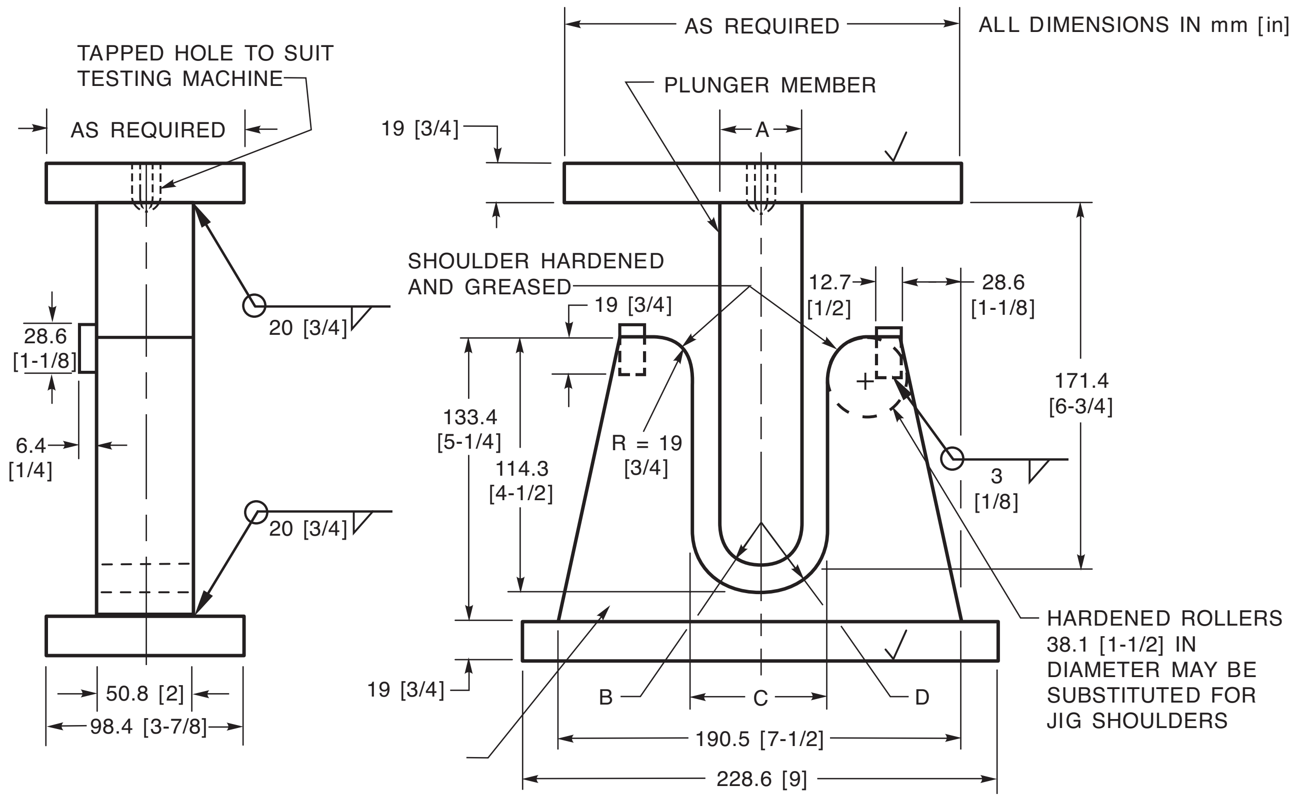


Note: Allowable variations shall be as follows:

Notch perpendicularity to edge	90° ± 2°
Adjacent sides	90° ± 10 min
Cross section dimensions	±0.075 mm [±0.003 in]
Length of specimen (L)	±0, –2.5 mm [–0.100 in]
Centering of notch (L/2)	±1 mm [0.04 in]: When an end-centering device is necessary to center the specimen in the anvil (see 9.3.2 in ASTM E23, *Standard Methods for Notched Bar Impact Testing of Metallic Materials*), it shall be necessary that the notch be accurately centered to ensure compliance with A1.10.1 (ASTM E23)
Angle of notch	±1°
Radius of notch	±0.025 mm [±0.001 in]
Depth of notch	±0.025 mm [±0.001 in]
Finish requirements	2 µm [63 µin] on notched surface and opposite face; 4 µm [125 µin] on other two surfaces

Note: Five test specimens shown, eight required for ESW and EGW.

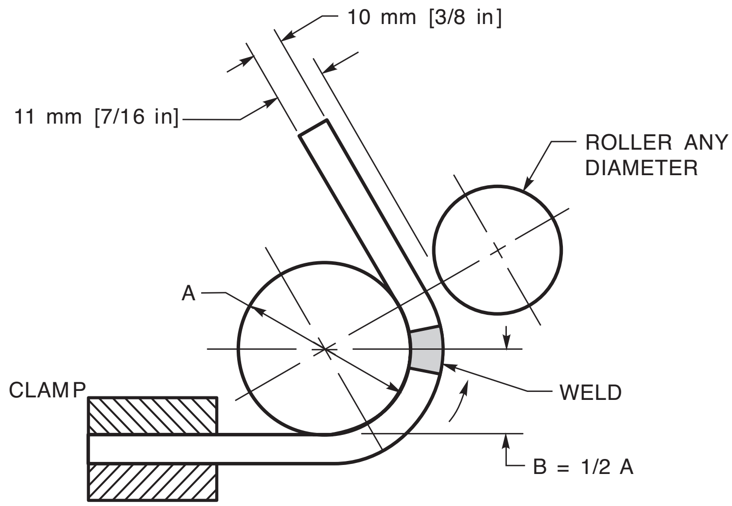
Figure 7.13—CVN Test Specimen—Type A (see 7.16.5)



Minimum Specified Base Metal Yield Strength, MPa [ksi]	A		B		C		D	
	mm	[in]	mm	[in]	mm	[in]	mm	[in]
345 [50] and under	38.1	[1-1/2]	19.0	[3/4]	60.3	[2-3/8]	30.2	[1-3/16]
Over 345 [50] to 620 [90]	50.8	[2]	25.4	[1]	73.0	[2-7/8]	36.6	[1-7/16]
620 [90] and over	63.5	[2-1/2]	31.8	[1-1/4]	85.7	[3-3/8]	42.6	[1-11/16]

Notes:
1. Plunger and interior die surfaces shall be machine-finished.
2. The diameter A of the plunger shall equal or exceed the weld face width (after machining). If this requirement cannot be met, see AWS B4.0M or B4.0 for guidance on adjusting the specimen thickness and fixture dimensions.

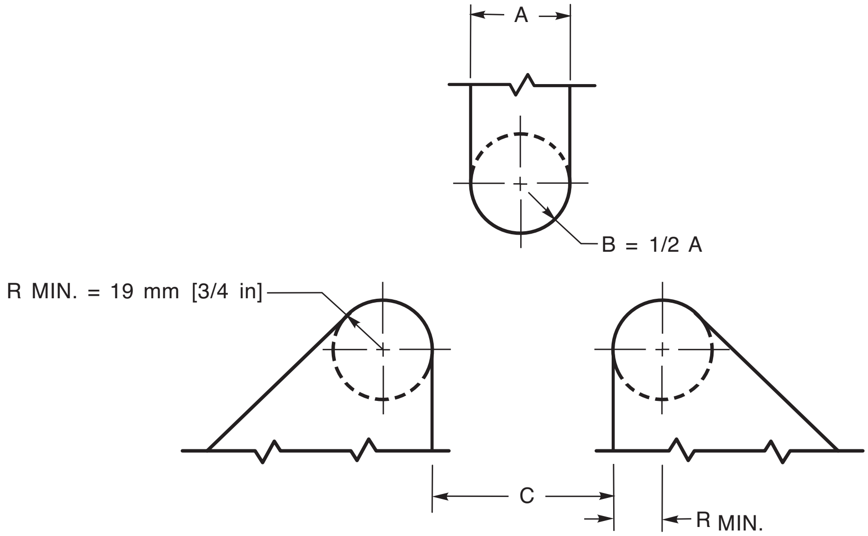
Figure 7.14—Guided Bend Test Jig (see 7.18.3)



Minimum Specified Base Metal Yield Strength, MPa [ksi]	A		B	
	mm	[in]	mm	[in]
345 [50] and under	38.1	[1-1/2]	19.0	[3/4]
Over 345 [50] to 620 [90]	50.8	[2]	25.4	[1]
620 [90] and over	63.5	[2-1/2]	31.8	[1-1/4]

Notes:
1. Minimum roller length shall be 50 mm [2 in].
2. Diameter A shall equal or exceed the weld face width (after machining). If this requirement cannot be met, see AWS B4.0M or B4.0 for guidance on adjusting the specimen thickness and fixture dimensions.

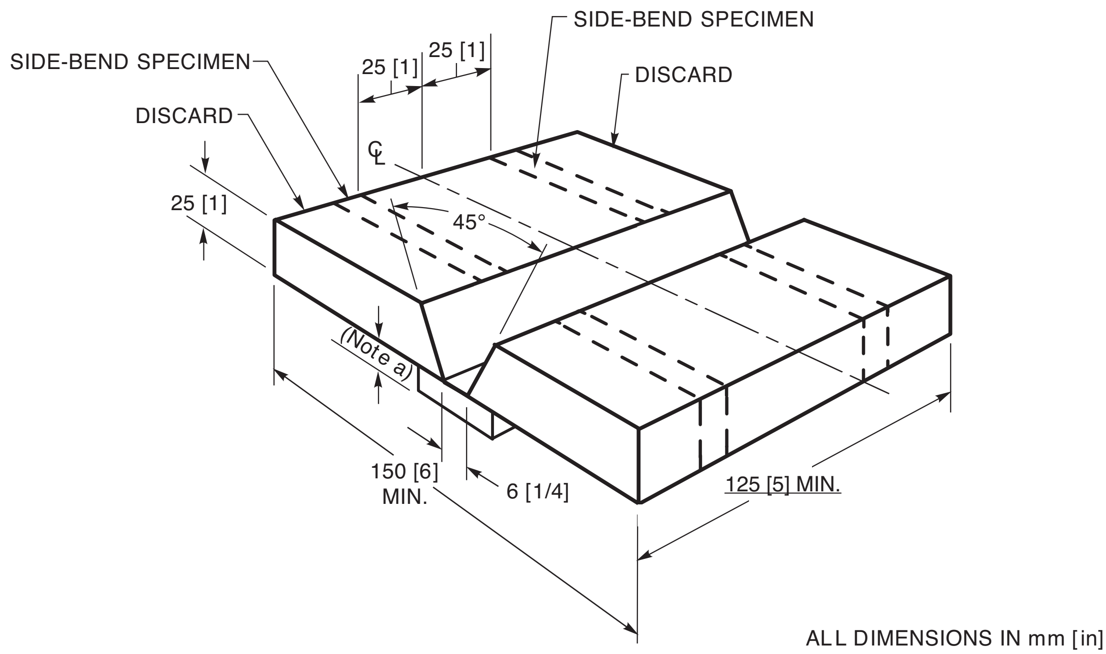
Figure 7.15—Alternate Wraparound Guided Bend Test Jig (see 7.18.3)



Minimum Specified Base Metal Yield Strength, MPa [ksi]	A		B		C	
	mm	[in]	mm	[in]	mm	[in]
345 [50] and under	38.1	[1-1/2]	19.0	[3/4]	60.3	[2-3/8]
Over 345 [50] to 620 [90]	50.8	[2]	25.4	[1]	73.0	[2-7/8]
620 [90] and over	63.5	[2-1/2]	31.8	[1-1/4]	85.7	[3-3/8]

Notes:
1. Minimum roller length (or shoulder width) shall be 50 mm [2 in].
2. Diameter A shall equal or exceed the weld face width (after machining). If this requirement cannot be met, see AWS B4.0M or B4.0 for guidance on adjusting the specimen thickness and fixture dimensions.

Figure 7.16—Alternate Roller-Equipped Guided Bend Test Jig for Bottom Ejection of Test Specimen (see 7.18.3)



[a] The backing thickness shall be 6 mm [1/4 in] min. to 10 mm [3/8 in] max.; backing width shall be 75 mm [3 in] min. when not removed for RT, otherwise 25 mm [1 in] min.

Note: When RT is used for testing, no tack welds shall be in test area.

Figure 7.17—Test Plate for Unlimited Thickness—Welder Qualification (see 7.23.1.2)

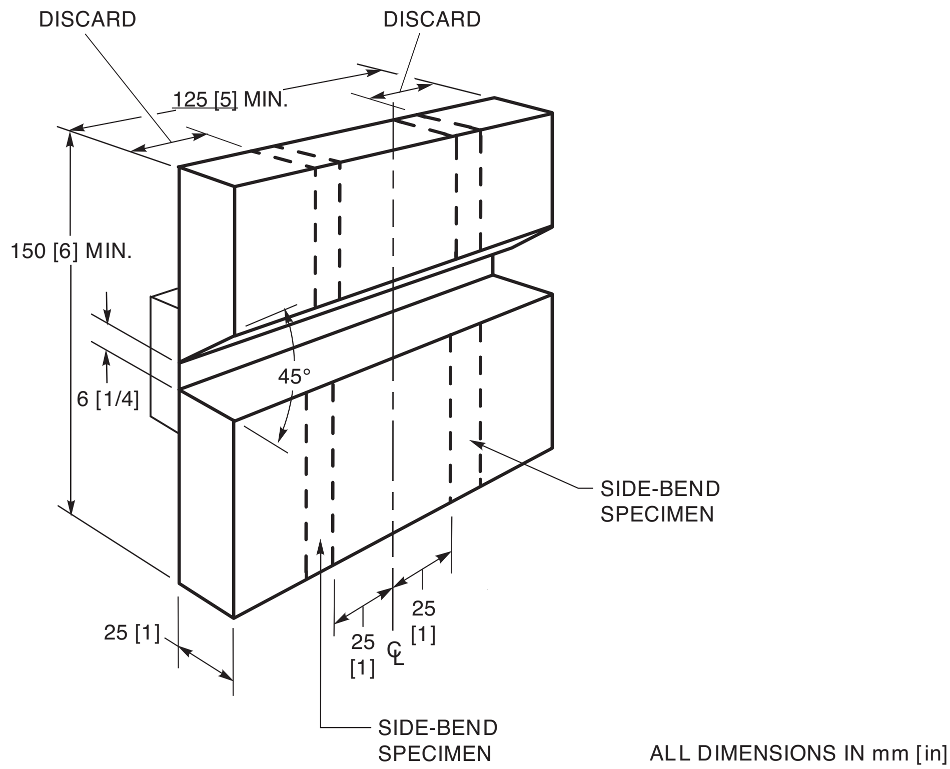


Figure 7.18—Optional Test Plate for Unlimited Thickness—Horizontal Position—Welder Qualification (see 7.23.1.2)

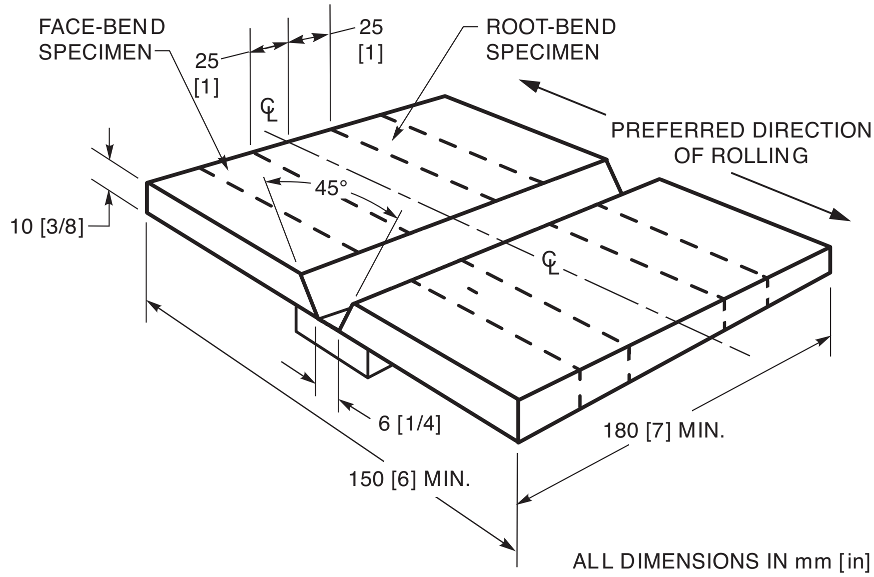
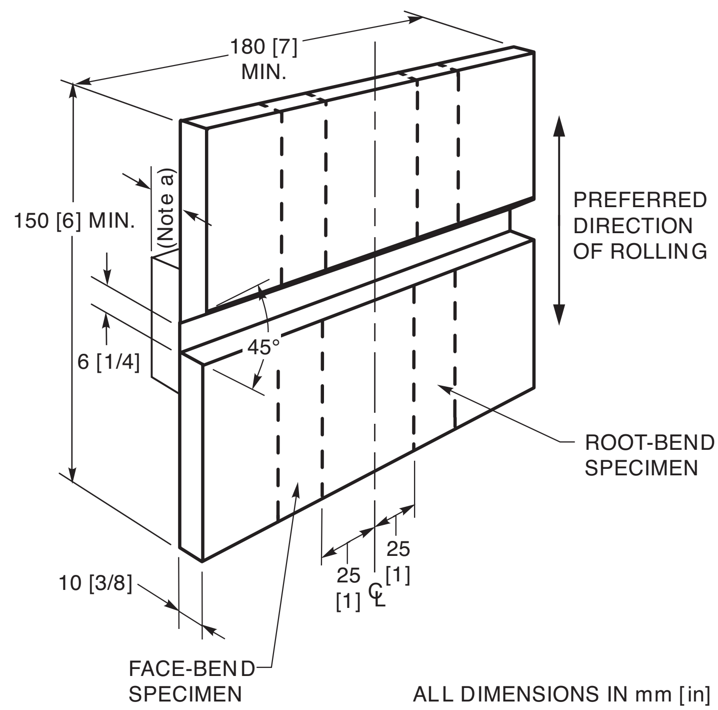


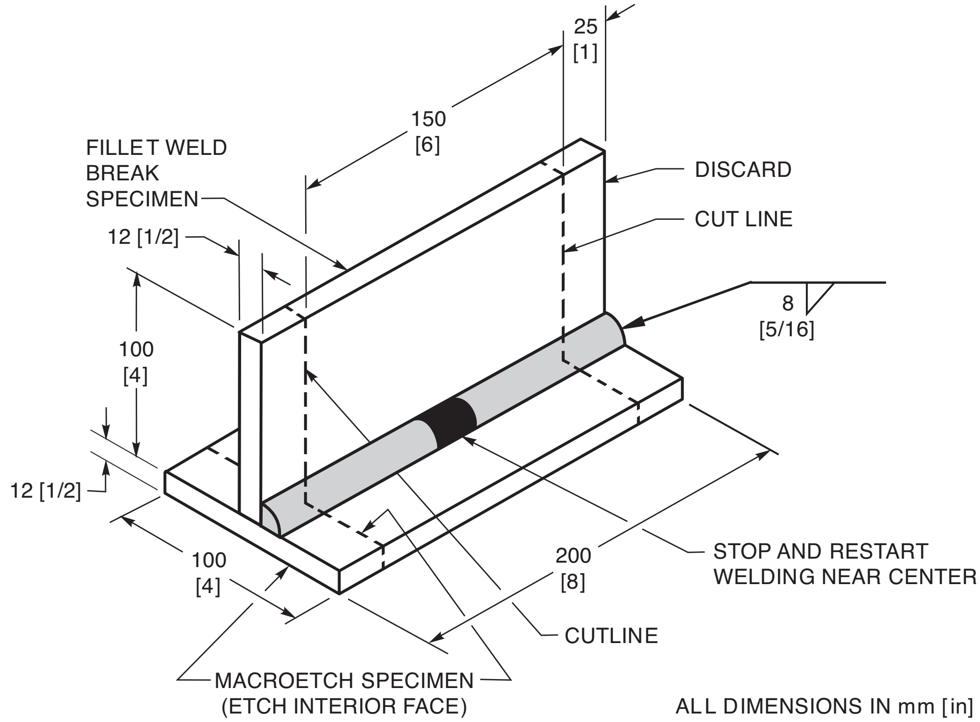
Figure 7.19—Test Plate for Limited Thickness—All Positions—Welder Qualification (see 7.23.1.3)



[a] The backing thickness shall be between 6 mm [1/4 in] min. and 10 mm [3/8 in] max.; backing width shall be 75 mm [3 in] max. for RT and 25 mm [1 in] min. for mechanical testing.

Note: When RT is used, no tack welds shall be in test area. Weld backing shall not be removed.

Figure 7.20—Optional Test Plate for Limited Thickness—Horizontal Position—Welder Qualification (see 7.23.1.3)



Note: Plate thickness and dimensions are minimum.

Figure 7.21—Fillet-Weld-Break and Macroetch Test Plate—Welder Qualification—Option 1 (see 7.23.1.4)

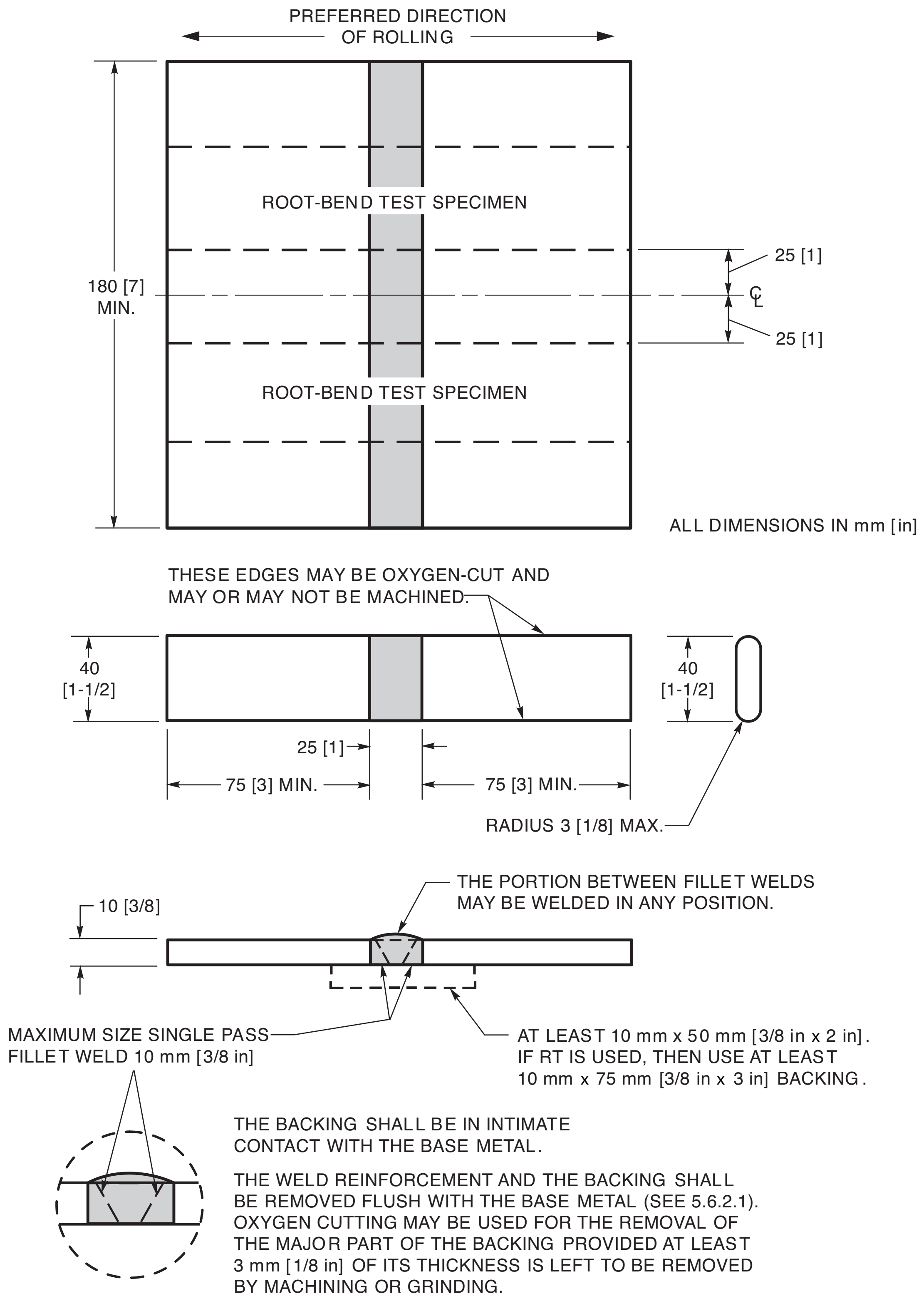


Figure 7.22—Fillet Weld Root-Bend Test Plate—Welder Qualification—Option 2 (see 7.23.1.4)

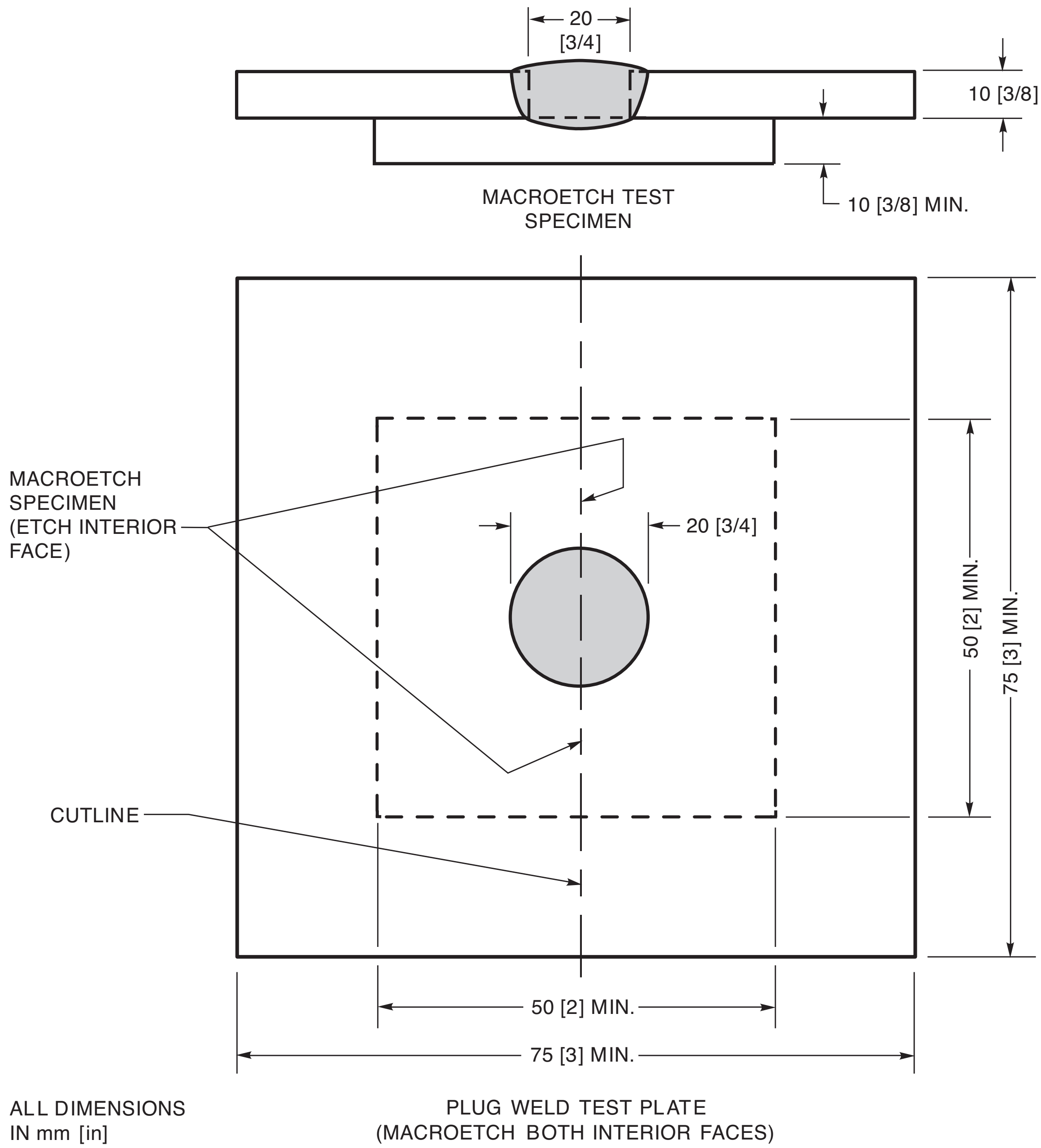
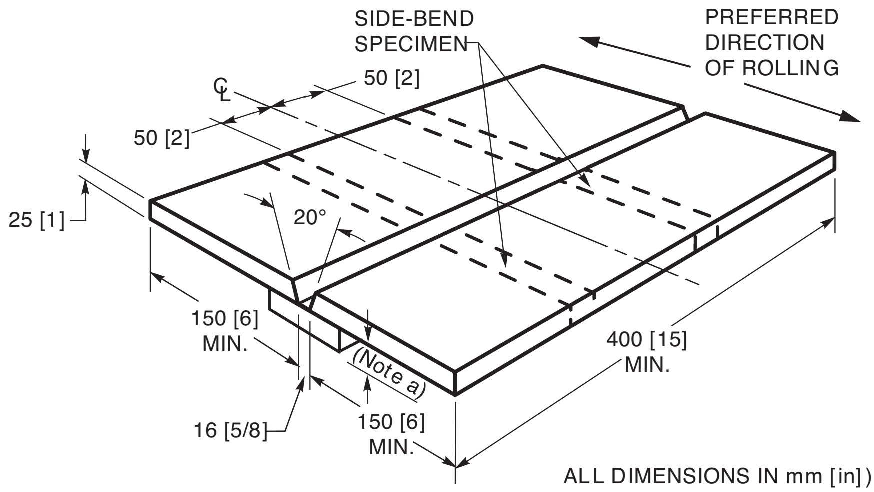


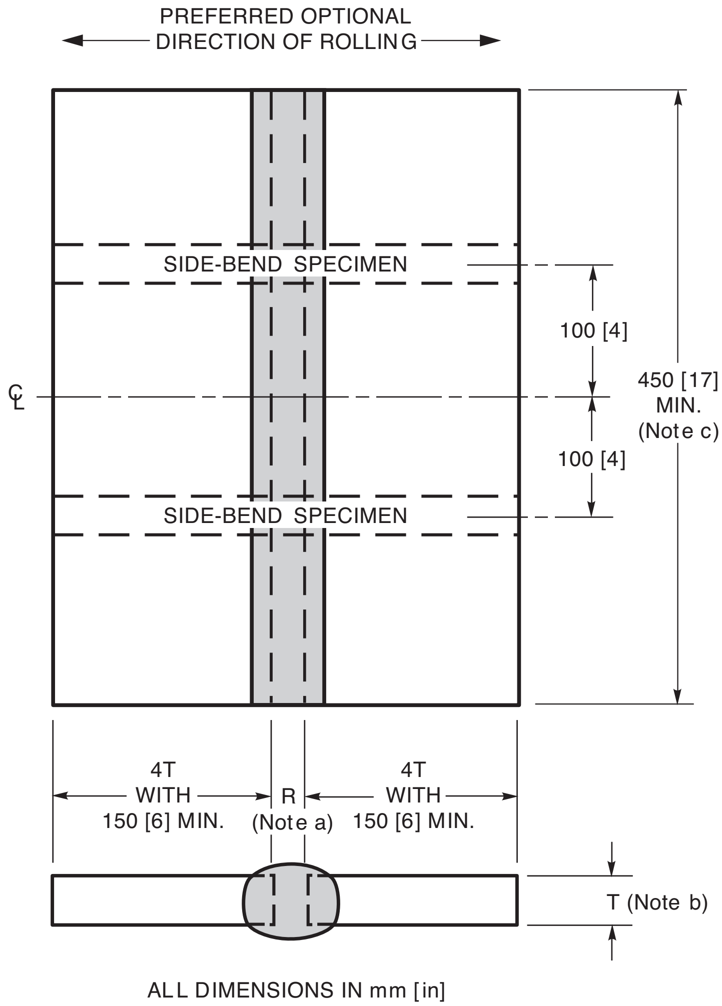
Figure 7.23—Plug Weld Macroetch Test Plate—Welder Qualification (see 7.23.1.5)



[a] The backing thickness shall be 10 mm [3/8 in] min. to 12 mm [1/2 in] max.; backing width shall be 75 mm [3 in] min. when not removed for RT, otherwise 40 mm [1-1/2 in].

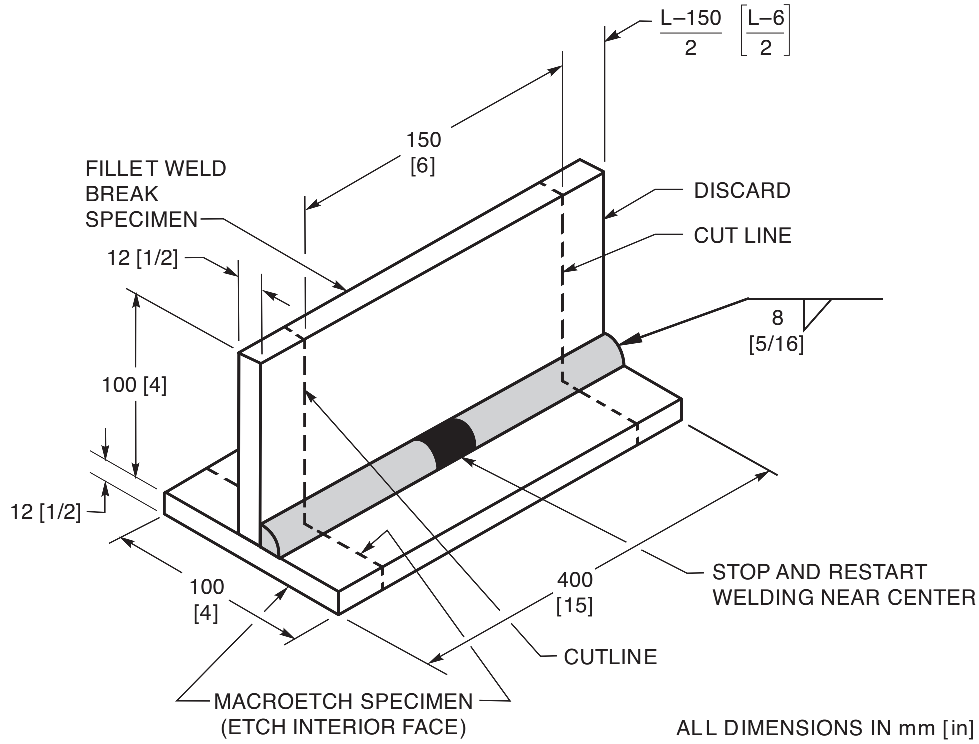
Notes:
1. When RT is used for testing, no tack welds shall be in test area.
2. The joint configuration of a qualified groove WPS may be used in lieu of the groove configuration shown here.

Figure 7.24—Test Plate for Unlimited Thickness—Welding Operator Qualification (see 7.23.2.1)



[a] Root opening "R" established by WPS.
[b] T = maximum to be welded in construction but need not exceed 38 mm [1-1/2 in].
[c] Extensions need not be used if joint is of sufficient length to provide 450 mm [18 in] of sound weld.

Figure 7.25—Butt Joint for Welding Operator Qualification—ESW and EGW (see 7.23.2.2)



Note: Plate thickness and dimensions are minimum.

Figure 7.26—Fillet-Weld-Break and Macroetch Test Plate—Welding Operator Qualification—Option 1 (see 7.23.2.4)

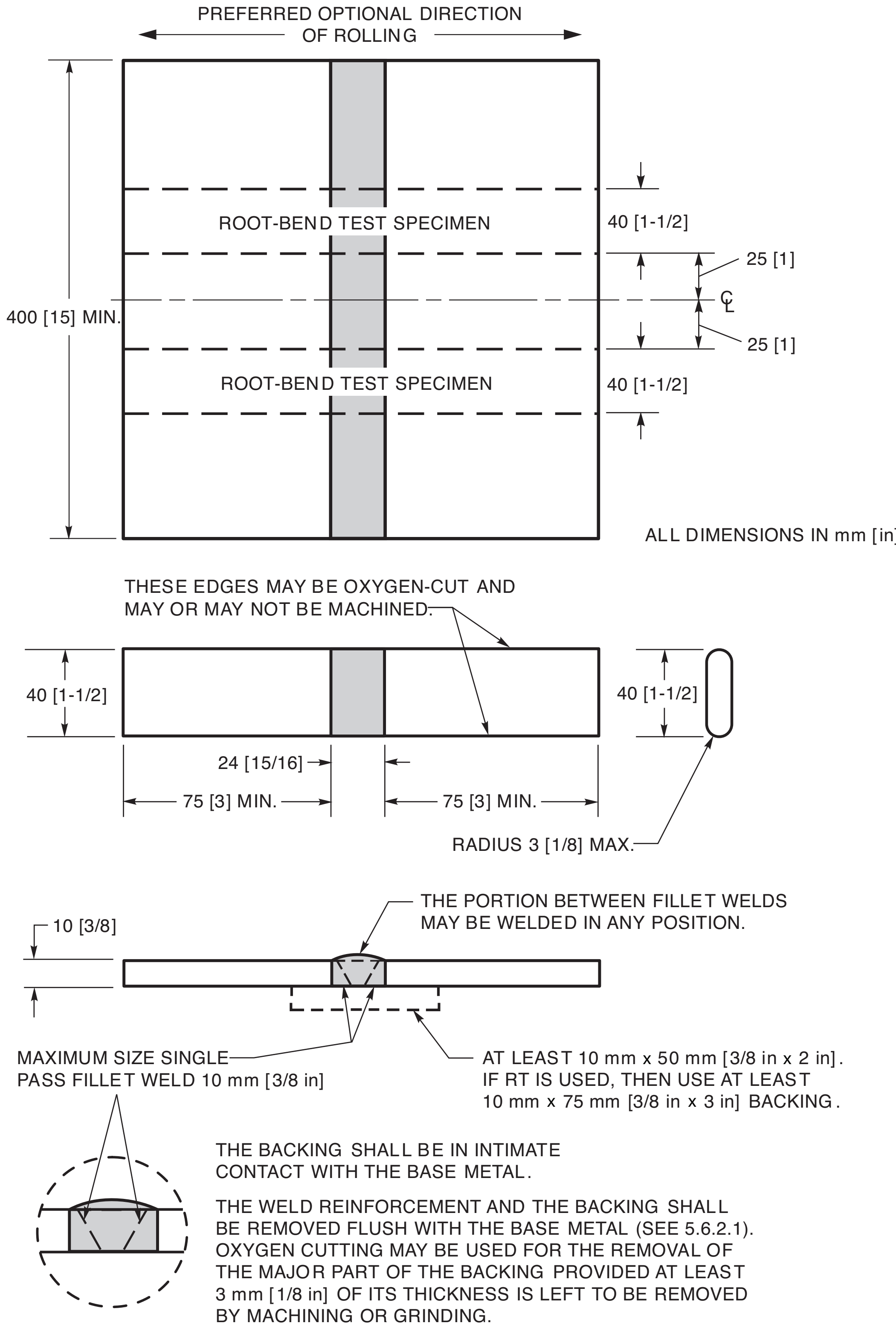


Figure 7.27—Fillet Weld Root Bend Test Plate—Welding Operator Qualification—Option 2 (see 7.23.2.4)

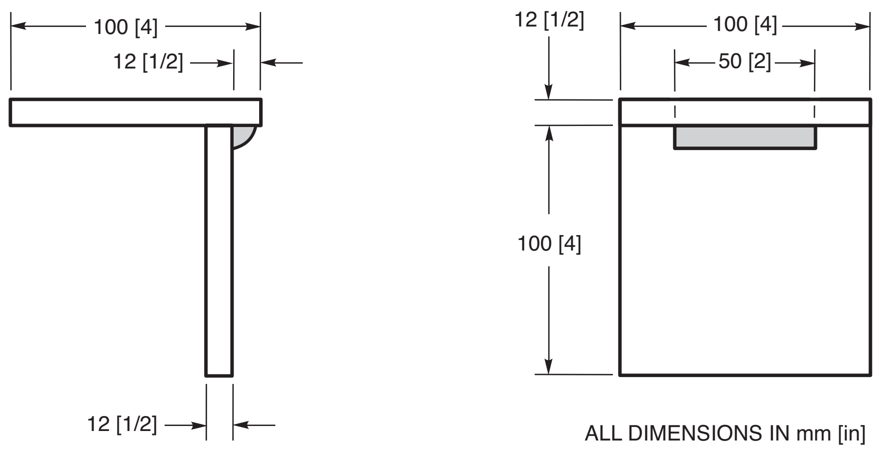


Figure 7.28—Fillet-Weld-Break Specimen—Tack Welder Qualification (see 7.25.3)

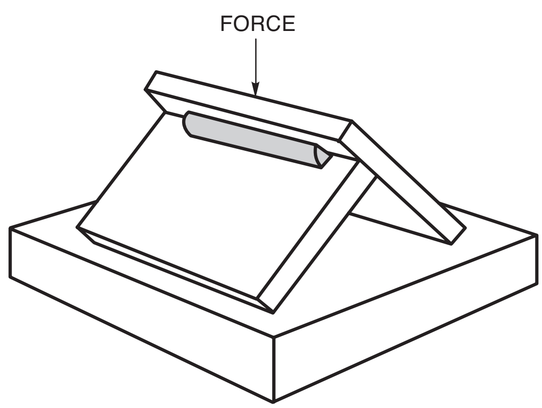


Figure 7.29—Method of Rupturing Specimen—Tack Welder Qualification (see 7.26.3.3)

8. Inspection

Part A
General Requirements

8.1 General

8.1.1 For the purpose of this code, quality control (QC) functions are performed by the Contractor and quality assurance (QA) functions are performed by the Owner. They shall be considered separate functions.

8.1.1.1 QC inspection, testing, and documentation shall be the responsibility of the Contractor. The Contractor shall perform inspection and testing prior to, during, and after assembly, and prior to, during, and after welding. The Contractor shall take all actions necessary to assure that materials and workmanship conform to the contract requirements.

8.1.1.2 QA inspection and testing to verify that furnished products satisfy the contract shall be the prerogative of the Engineer.

8.1.2 Inspector—Definition

8.1.2.1 The QC Inspector shall be the duly designated person who acts for and in behalf of the Contractor on inspection, testing, and quality matters within the scope of the contract documents. When there are several persons performing QC inspection and testing, a supervising Inspector shall be designated as the QC Inspector.

8.1.2.2 The QA Inspector shall be the duly designated person who acts for and on behalf of the Engineer and Owner on all matters within the scope of the contract documents and the limit of authority delegated by the Engineer.

8.1.2.3 The term *Inspector*, when used without further qualification, shall apply equally to the Contractor's QC and Owner's QA as defined in 8.1.2.1 and 8.1.2.2.

8.1.3 Inspection Personnel Qualification

8.1.3.1 All Inspectors responsible for acceptance or rejection of materials and workmanship shall be qualified as follows:

(1) The Inspector shall be an AWS Certified Welding Inspector (CWI) qualified and certified in conformance with the provisions of AWS QC1, *Standard for AWS Certification of Welding Inspectors*, or

(2) The Inspector shall be qualified by the Canadian Welding Bureau (CWB) to the Level II or Level III requirements of the Canadian Standard Association (CSA) standard W178.2, *Certification of Welding Inspectors*, or

(3) The Inspector shall be an engineer or technician who, by training and experience in metals fabrication, inspection and testing, is acceptable to the Engineer as an equivalent to (1) or (2).

8.1.3.2 An Inspector, previously certified as a welding Inspector under the provisions of AWS QC1 or CSA standard W178.2, Level II or III, may serve as an Inspector for this work, provided there is acceptable documentation that the Inspector has remained active as an Inspector of welded structural steel fabrication since last being certified and there is no reason to question the Inspector's ability.

8.1.3.3 The Inspector may be supported by Assistant Inspectors who may perform specific inspection functions under the supervision of the Inspector. Assistant Inspectors are not required to be qualified in accordance with other subclauses of 8.1.3 but shall be qualified by training and experience to perform the specific functions to which they are assigned. The work of Assistant Inspectors shall be regularly monitored, generally on a daily basis, by the Inspector.

8.1.3.4 **Personnel Qualification.** Personnel performing NDT, other than visual examination, shall be certified in conformance with the American Society for Nondestructive Testing's (ASNT) *Recommended Practice No.* SNT-TC-1A, *Personnel Qualification and Certification in Nondestructive Testing*, or an equivalent satisfactory to the Engineer. Certification of Level I and Level II individuals shall be performed by the ASNT Central Certification Program (ACCP), or a Level III individual who has been certified by (1) ASNT, or (2) has the education, training, experience, and has successfully passed the written examination prescribed in ASNT SNT-TC-1A. Individuals who perform NDT shall be certified as:

(1) NDT Level II, or

(2) NDT Level I working under the direct supervision of an individual qualified for NDT Level II or NDT Level III.

(3) NDT Level III and qualified per ASNT SNT-TC-1A as a Level II for NDT performed.

8.1.3.5 The Engineer shall have the authority to verify the qualifications of Inspectors and NDT personnel to specified levels by tests or other means.

8.1.3.6 Personnel performing NDT per 8.1.3.4 need not be qualified per 8.1.3.1 but shall have adequate vision per 8.1.3.7.

8.1.3.7 Inspectors, Assistant Inspectors, and personnel performing NDT shall have passed an eye examination, with or without corrective lenses, to prove near vision acuity of Jaeger J–2 at 300 mm to 430 mm [12 in to 17 in]. Vision tests shall be required every three years, or less if necessary, to demonstrate adequacy.

8.1.4 The Inspector shall be furnished complete detailed drawings showing the size, length, type, and location of all welds to be made. The Inspector shall be furnished with the portion of the contract documents which describes material and quality requirements for the products to be fabricated or erected, or both.

8.1.5 The Inspector shall be notified in advance of the start of fabrication/erection operations subject to inspection and verification.

8.2 Inspection of Materials

The Contractor shall make certain that only materials conforming to the requirements of the contract documents are used.

8.3 Inspection of WPS Qualification and Equipment

8.3.1 Prior to the use of a WPS in production welding, the Inspector shall make certain that the WPS is qualified in conformance with Clause 7 of this code, that each welding operation is covered by a written WPS, and that such WPSs are available to the welders and Inspectors for reference.

8.3.2 The Inspector shall inspect the welding and cutting equipment to be used in the work to verify that it conforms to the requirements of 5.1.2.

8.4 Inspection of Welder, Welding Operator, and Tack Welder Qualifications

8.4.1 The Inspector shall allow welding to be performed only by welders, welding operators, and tack welders who are qualified in conformance with the requirements of Clause 7, and shall verify that their qualifications authorize them to use the WPSs specified for the work, or shall make certain that each welder, welding operator, or tack welder has previously demonstrated such qualification under supervision acceptable to the Engineer.

8.4.2 When the quality of work by a welder, welding operator, or tack welder appears to be below the requirements of this code, the Inspector may require that the welder, welding operator, or tack welder demonstrate an ability to produce sound welds by means of a simple test, such as the fillet weld break test, or by requiring complete requalification in conformance with Clause 7. (See 7.26.3.3).

8.4.3 The Inspector shall require requalification of any welder, welding operator, or tack welder whose qualification is not current by the requirements of this code.

8.4.4 When qualifying welders, welding operators, and tack welders, a QC Inspector shall observe the qualification tests and the results shall be documented and signed.

8.5 Inspection of Work and Records

8.5.1 The Inspector shall make certain that the size, length, and location of all welds conform to the requirements of this code and to the detail drawings and that no unspecified welds have been added without approval.

8.5.2 The Inspector shall make certain that only WPSs meeting the provisions of Clause 7 are used.

8.5.3 The Inspector shall make certain that electrodes are used only in the positions and with the type of welding current and polarity for which they are classified.

8.5.4 The QC Inspector shall, at suitable intervals, observe the joint preparation, assembly practice, welding techniques, and performance of each welder, welding operator, and tack welder to make certain that applicable requirements of this code are met. The QC Inspector shall examine the work to make certain that it meets the requirements of Clause 5 and 8.26. The size and contour of welds shall be measured using suitable gages. Visual inspection for cracks in welds and base metal, and for other discontinuities should be aided by strong light magnifiers, or such other devices as may be helpful. Subject to the authority granted, the QC Inspector shall determine acceptability of materials and workmanship based on contract requirements. Acceptance criteria different from those described in this code may be used with documented approval by the Engineer.

8.5.5 The Inspector shall identify with a distinguishing mark or adequate document control as approved by the Engineer all parts or joints that the Inspector has inspected and approved.

8.5.6 The Inspector shall keep a record of qualifications of all welders, welding operators, and tack welders; all WPS qualifications or other tests that are made; the control of welding materials and equipment; and such other information as may be required.

8.5.7 For NDT, the Inspector shall verify that personnel qualifications, equipment calibrations, and procedures are current. The Inspector is authorized to witness NDT, evaluate the test results, monitor repairs, and approve or reject welds.

8.5.8 The Inspector shall record the locations of inspected areas and the findings of all NDT, together with detailed descriptions of all repairs made.

8.6 Obligations of the Contractor

8.6.1 The Contractor shall allow access to the project fabrication facility by QA personnel. The Contractor shall cooperate with QA personnel and provide ready access to QC inspection records.

8.6.2 The Contractor shall be responsible for visual inspection and NDT described in 8.7 and necessary correction of all deficiencies in materials and workmanship in conformance with the requirements of Clause 5 and 8.26 and as specified elsewhere in contract documents.

8.6.3 The Contractor shall correct deficiencies in materials and workmanship identified by the Inspector, to satisfy the contract documents.

8.6.4 In the event that faulty welding or its removal for rewelding damages the base metal so that in the judgment of the Engineer, its retention is not in conformance with the intent of the contract documents, the Contractor shall remove and replace the damaged base metal or shall compensate for the deficiency in a manner approved by the Engineer.

8.6.5 If NDT not specified in the original contract agreement is subsequently requested by the Engineer, the Contractor shall perform any requested testing or shall allow any requested testing to be performed. Costs shall be negotiated by the Owner and the Contractor. Responsibility for the cost of extra work shall lie with the Owner. However, if such testing should disclose an attempt to defraud or reveal gross nonconformance to this code, repair work shall be done at the Contractor's expense.

8.6.6 The Contractor shall schedule NDT to facilitate attendance by the QA Inspector. The QA Inspector shall be advised by the Contractor of operational and NDT schedules and scheduled changes.

8.7 Nondestructive Testing (NDT)

The Contractor shall perform NDT on welds to primary components of main members using the methods and frequencies required in Table 8.1. Subclauses 8.7.1 through 8.7.4 contain additional requirements. Where Table 8.1 requires only partial testing, the Inspector shall select the inspection locations, after welding is complete. The choice of the lot basis or per-joint basis of partial testing, where both options are given, shall be at the Contractor's option.

8.7.1 CJP groove welds in main members shall be tested by NDT. Unless otherwise provided, RT shall be used for examination of CJP groove welds in butt joints subject to calculated tension or reversal of stress. All CJP groove welds in T- and corner joints shall be tested by UT. When CJP groove welds in butt joints subject only to compression or shear require testing, either RT or UT shall be used, subject to Contractor preference and contract requirements.

8.7.2 Partial NDT of Transverse Butt Joints in Webs. If partial NDT of transverse butt joints in webs is required and a defect is found in the tested length, the uninspected remainder of the weld shall be tested by UT or RT as required for the type of loading by Table 8.1.

If a defect is found in any test length of a weld in a transverse butt joint in a web, the remainder of the weld shall be tested by UT or RT as required for the type of loading by Table 8.1.

8.7.3 CJP Groove Welds Subject to Compression or Shear. Requirements for 25% testing of joints in compression or shear given in Table 8.1 shall be satisfied by either 8.7.3.1 or 8.7.3.2.

8.7.3.1 Testing on Per-Joint Basis. 25% of each joint in compression or shear shall be tested. If a defect is found in any test length of a weld, the entire length shall be tested by UT or RT.

8.7.3.2 Testing on Lot Basis. 25% of the total joints in compression or shear in a lot as defined in 8.7.3.3 shall be tested for their entire length. Joints tested on a lot basis shall be distributed throughout the work and shall total at least 25% of the total compression or shear weld length for the lot. If defects are found in 20% or more of the compression or shear joints tested in a lot, all compression and shear joints in that lot shall be tested for their full length by UT or RT.

8.7.3.3 NDT Lot. A *lot* is defined as those joints that were welded in conformance with the same approved WPS, are subject to the same type of design stress (tension, compression, shear), and are examined with NDT as a group.

8.7.4 Fillet Welds and PJP Groove Welds. Requirements for 10% testing given in Table 8.1 shall be satsified by 8.7.4.1 or 8.7.4.2, as applicable.

8.7.4.1 Long Welds. For welds 3 m [10 ft] or longer, at least 300 mm [12 in] shall be tested in every 3 m [10 ft] length. If a defect is found in any test length of weld, the full length of the weld, or 1.5 m [5 ft] on both sides of the test length, whichever is less, shall be tested.

8.7.4.2 Short Welds. Welds less than 3 m [10 ft] in length shall be tested on either a per-joint or per-lot basis in accordance with either 8.7.4.2(1) or 8.7.4.2(2), respectively.

(1) Testing on Per-Joint Basis. At least 300 mm [12 in] of each weld shall be tested. If a defect is found in any test length, the full length shall be tested.

(2) Testing on Lot Basis. 10% of the total joints in a lot as defined in 8.7.3.3 shall be tested for their full length. Joints tested on a lot basis shall be distributed throughout the work and shall total at least 10% of the applicable fillet weld or PJP weld length. If defects are found in 20% or more of the joints tested in a lot, all joints in that lot shall be tested for their full length.

8.7.5 After weld repairs are complete, additional NDT shall be performed to ensure that the repairs are satisfactory. This testing shall include the repaired area plus at least 50 mm [2 in] on each end of the repaired area.

8.7.6 Welds tested with NDT that do not meet the requirements of this code shall be repaired by the methods of 5.7.

8.7.7 When RT is used, the procedure and technique shall be in conformance with Part B of this clause.

8.7.8 When MT is used, the procedure and techniques shall be in conformance with the dry powder MT of welds using the prod method or the yoke method.

8.7.8.1 The prod method shall be performed in conformance with ASTM E709, *Standard Guide for Magnetic Particle Testing*, and the standards of acceptance shall be in conformance with 8.26.

(1) When the prod method is used to test steels with a minimum specified yield strength of 345 MPa [50 ksi] or greater, aluminum prods shall be used on the test equipment. Copper prods shall not be used on such steels.

(2) Arcing shall be minimized by following the proper testing procedures.

8.7.8.2 The yoke method shall be performed in conformance with ASTM E709, and the standard of acceptance shall be in conformance with 8.26.

(1) Testing by the yoke method shall be performed using half-wave rectified DC, DC pulsed, or AC.

(2) Electromagnetic yokes shall have lifting forces conforming to the following requirements:

	Yoke Pole Leg Spacing (YPS), mm [in]	
Current Type	$50 \leq YPS < 100$ [$2 \leq YPS < 4$]	$100 \leq YPS \leq 150$ [$4 \leq YPS \leq 6$]
AC	45 N [10 lb]	45 N [10 lb]
Half Wave Rectified DC and Pulsed DC	135 N [30 lb]	225 N [50 lb]

8.7.8.3 Prior to MT, the surface shall be examined, and any adjacent area within at least 25 mm [1 in] of the surface to be tested, shall be dry and free of contaminants such as oil, grease, loose rust, loose sand, loose scale, lint, thick paint, welding flux, and weld spatter. Thin nonconductive coatings such as paint in the order of 0.02 mm to 0.05 mm [1 mil to 2 mils] that do not interfere with the formation of indications may remain, but they must be removed at all points where electrical contact is to be made.

Cleaning may be accomplished by detergents, organic solvents, descaling solutions, paint removers, vapor degreasing, sand or grit blasting, and ultrasonic cleaning methods.

8.7.8.4 The prod or poles shall be oriented in two directions approximately 90° apart at each inspection point, to detect both longitudinal and transverse discontinuities. The prod or pole position shall overlap as testing progresses to ensure 100% inspection of the areas to be tested.

8.7.8.5 A report of MT shall be prepared and furnished to the Engineer.

(1) The report shall include the following minimum information:

(a) Part identification

(b) Examination procedure number (if applicable)

(c) Date of examination

(d) Technician's name, certification level, and signature

(e) Name and signature of Contractor's or Owner's Inspectors, or both, who witnessed the examination

(f) Examination results

(g) Equipment make and model

(h) Yoke or prod spacing used

(i) Particles (manufacturer's name) and color

(2) One copy shall be furnished to the Contractor for the Owner.

8.7.9 For detecting discontinuities that are open to the surface, PT may be used. The standard methods set forth in ASTM E165 shall be used for PT, and the standards of acceptance shall be in conformance with 8.26.

8.7.10 Phased-array UT (PAUT) in accordance with Annex J may be substituted for conventional UT (as described in Part C of this clause).

Part B
Radiographic Testing (RT) of Groove Welds in Butt Joints

8.8 Extent of Testing

The provisions of 8.7 shall identify the minimum extent of RT.

8.9 General

8.9.1 Procedures and Standards. The procedures and standards set forth in Part B govern radiographic testing of welds. The requirements described herein are specifically for testing groove welds in butt joints in plate, shapes, and bars by X-ray or gamma ray sources. The methods shall conform to ASTM E94, *Standard Guide for Radiographic Examination* and; ASTM E1032, *Standard Test Method for Radiographic Examination of Weldments*. The digital image archival method shall be in accordance with ASTM E2339, *Standard Practice for Digital Imaging and Communication in Nondestructive Evaluation (DICONDE)*.

8.9.2 Variations. Variations in testing procedures, equipment, and acceptance standards may be used upon agreement between the Contractor and the Engineer. Such variations include, but are not limited to, the following:

(1) RT of fillet, T-, and corner welds

(2) Reduction of source-to-film distance to less than that permitted in 8.10.5.

(3) Unusual application of film

(4) Unusual Image Quality Indicator applications (including film side IQIs)

(5) RT of thicknesses greater than 150 mm [6 in]

(6) Film types other than those permitted in 8.10.4

(7) Density or brightness requirements other than those permitted in 8.10.11.1

(8) Unusual exposure, film development, or image processing requirements or techniques

(9) Unusual viewing techniques

8.10 RT Procedure

8.10.1 Procedure. Radiographic film and digital images shall be made using a single source of either X- or gamma radiation. The RT sensitivity shall be judged based on hole-type or wire IQI images. RT technique and equipment shall provide sufficient sensitivity to clearly delineate the required IQIs and the essential holes or wire sizes as described in 8.10.7, Tables 8.2A and 8.2B, and Figures 8.1E and 8.1F. Identifying letters and numbers shall show clearly in the radiographic film or digital image.

8.10.1.1 Digital Radiography. At the option of the Contractor, the digital radiography method shall be either computed radiography (CR) using a photostimulable phosphor plate, more commonly known as a storage phosphor imaging plate (SPIP), or direct radiography (DR) using a Digital Detector Array (DDA).

(1) CR shall comply with ASTM E2033, *Standard Practice for Computed Radiology (Photostimulable Luminescence Method)* and ASTM E2445, *Standard Practice for Qualification and Long-Term Stability of Computed Radiology Systems.*

(2) DR shall comply with ASTM E2698, *Standard Practice for Radiological Examination Using Digital Detector Arrays* and ASTM E2737, *Standard Practice for Digital Detector Array Performance Evaluation and Long-Term Stability*

8.10.2 RT shall be performed in conformance with all applicable safety requirements.

8.10.3 Removal of Reinforcement. When the contract documents require the removal of weld reinforcement, it shall be removed in accordance with 5.6.2.1 prior to RT. Other weld surface conditions and surfaces adjacent to the weld may be finished at the Contractor's option to improve the radiographic image.

8.10.3.1 Weld tabs (extension bars and run-off plates) shall be removed prior to RT, unless otherwise approved by the Engineer.

8.10.3.2 When required by 5.13 or other provisions of the contract documents, steel backing shall be removed and the surface shall be finished flush prior to RT. Finishing shall be as described in 5.6.2.1.

8.10.3.3 When weld reinforcement or backing, or both, are not removed and hole-type or wire IQI alternate placement is not used, steel shims that extend at least 3 mm [1/8 in] beyond three sides of the required hole-type or wire IQI shall be placed under the IQI so that the total thickness of steel between the IQI and the film is approximately equal to the average thickness of the weld measured through its reinforcement and backing.

8.10.4 Radiographic Film. Radiographic film shall be ASTM System Class I or II as described in ASTM E1815. Lead foil screens shall be used as described in ASTM E94. Fluorescent screens shall be prohibited.

8.10.5 Technique. Radiographs shall be made with a single source of radiation centered as near as practical with respect to the length and width of that portion of the weld being examined.

8.10.5.1 Geometric Unsharpness. Gamma ray sources, regardless of size, shall be capable of meeting the geometric unsharpness limitation of ASME *Boiler and Pressure Vessel Code*, Section V, Article 2.

8.10.5.2 Source-to-Subject Distance. The source-to-subject distance shall not be less than the total length to be interpreted in a single plane of film, SPIP, or DDA. This provision does not apply to panoramic exposures made under the provisions of 8.9.

8.10.5.3 Source-to-Subject Distance Limitations. The source-to-subject distance shall not be less than seven times the thickness of weld plus reinforcement and backing, if any, nor such that the inspecting radiation shall penetrate any portion of the weld represented in the radiograph at an angle greater than 26–1/2° from a line normal to the weld surface.

8.10.6 Sources. X-ray units, 600 kVp potential maximum, and Iridium 192 may be used as a source for all RT, provided they have adequate penetrating ability. Cobalt 60 shall be used as an RT source only when the steel being radiographed exceeds 75 mm [3 in] in thickness. Other RT sources shall be subject to the approval of the Engineer.

8.10.7 IQI Selection and Placement. Hole-type or wire IQIs shall show clearly on each radiograph. The minimum number and their required locations shall be as follows:

For welds joining nominally equal thicknesses, where a radiograph represents 250 mm [10 in] or greater of weld length, two IQIs placed, as shown in Figure 8.1A; where a radiograph represents less than 250 mm [10 in] of weld, one hole-type or wire IQI placed as shown in Figure 8.1B.

For welds at a transition in thickness, where a radiograph represents 250 mm [10 in] or greater of weld length, two hole-type or wire IQIs on the thinner plate and one hole-type or wire IQI on the thicker plate, or two wire IQIs at the alternate wire IQI placement locations each as shown in Figure 8.1C; when a radiograph represents less than 250 mm [10 in] of weld length, one hole-type or wire IQI on each plate or one wire IQI at the alternate wire IQI placement location shown in Figure 8.1D.

8.10.7.1 Hole-type IQIs or wire IQI shall be placed on the source side with hole-type IQI parallel to the weld joint and holes at the outer edge of the area being radio-graphed. IQI wires shall be perpendicular to the joint with the smallest wire on the outer edge of the area being radiographed.

8.10.7.2 The thickness of hole-type IQIs or wire IQI set and the essential hole or wire shall be as described in Tables 8.2A and 8.2B. A smaller essential hole or wire or a thinner hole-type IQI, or a wire IQI using smaller wires may be selected by the Contractor, provided all other provisions for RT are met.

8.10.7.3 Thickness shall be measured as T1 or T2, or both, at the locations shown in Figure 8.1A, 8.1B, 8.1C, or 8.1D and may be increased to provide for the thickness of allowable weld reinforcement, provided shims are used as described in 8.10.3.3. Steel backing shall not be considered part of the weld or reinforcement in hole-type IQI or wire IQI selection.

8.10.7.4 Hole-type IQIs shall be manufactured from steel, preferably stainless steel, and shall conform to dimensions shown in Figure 8.1E. For more detailed information, see ASTM E1025, *Practice for Design, Manufacture, and Material Grouping Classification of Hole-Type Image Quality Indicators (IQI) Used for Radiography*. Each IQI shall be manufactured with three holes, one of which shall be of a diameter equal to twice the IQI thickness (2T). The diameter of the two remaining holes shall be selected by the manufacturer. They shall ordinarily equal one time (1T) and four times (4T) the IQI thickness. IQI designations 10 through 25 shall contain a 4T hole.

8.10.7.5 Wire IQIs shall be manufactured in conformance with Figure 8.1F. For more detailed information, see ASTM E747.

8.10.8 Technique. Welded joints shall be radiographed and the film, SPIP, or DDA indexed by methods that will provide complete and continuous inspection of the joint within the limits specified to be examined. Joint limits shall show clearly in the radiographic film or digital images. Short film, short screens, excessive undercut by scattered radiation, or any other process that obscures portions of the total weld length shall render the radiographic film or digital image unacceptable.

8.10.8.1 Film or Plate Length. Film, SPIPs, and DDAs shall have sufficient length and shall be placed to provide at least 12 mm [1/2 in] of imaging media beyond the projected edge of the weld.

8.10.8.2 Overlapping Images. Welds longer than 350 mm [14 in] may be radiographed by overlapping film cassettes and making a single exposure; or by making separate exposures using DDAs or using single-film cassettes with either SPIPs or conventional film.

8.10.8.3 Backscatter. To check for backscattered radiation, a lead symbol "B," 12.7 mm [1/2 in] high, and 1.6 mm [1/16 in] thick, shall be attached to the back of each film cassette or SPIP holder. If the "B" image appears on the radiographic film or digital image, the film or image shall be considered unacceptable.

8.10.9 Film, SPIP, and DDA Width. Film, SPIP, and DDA widths shall be sufficient to depict all portions of the weld joint, including the HAZs, and shall provide sufficient additional space for the required hole-type or wire IQIs and film identification without infringing on the area of interest.

8.10.10 Quality of Radiographic Film and Digital Images. All radiographic film and digital images shall be free from imperfections and artifacts to such extent that they cannot mask or be confused with the image of any discontinuity in the area of interest.

8.10.10.1 Radiographic imperfections include but are not limited to the following:

(1) Fogging

(2) Processing defects such as streaks, water marks, or chemical stains

(3) Scratches, finger marks, crimps, dirtiness, static marks, smudges, or tears

(4) Loss of detail due to poor screen-to-film contact

(5) False indications due to defective screens, SPIP, DDA, or internal faults

(6) Artifacts due to non-functional pixels, including those resulting from dead or blooming pixels.

8.10.11 Density, Brightness, and Contrast Limitations

8.10.11.1 Radiographic Film. The transmitted film density through the radio-graphic image of the body of the required IQI(s) and the area of interest shall be 1.8 minimum for single-film viewing for radiographs made with an X-ray source and 2.0 minimum for radiographs made with a gamma ray source. For composite viewing of double-film exposures, the minimum density shall be 2.6. Each radiograph of a composite set shall have a minimum density of 1.3. The maximum density shall be 4.0 for either single or composite viewing.

(1) H & D Density. The density measured shall be H & D density (radiographic density), which is a measure of film blackening, expressed as:

$D = \log (I_o/I)$

where

D = H & D (radiographic) density
I_o = light intensity on the film, and
I = light transmitted through the film

(2) Thickness Transitions. When weld transitions in thickness are radiographed and the ratio of the thickness of the thicker section to the thickness of the thinner section is 3 or greater, radiographs should be exposed to produce single-film densities of 3.0 to 4.0 in the thinner section. When this is done, the minimum density requirements of 8.10.11.1 shall be waived, unless otherwise provided in the contract documents.

8.10.11.2 Digital Image Sensitivity Range. The contrast and brightness ranges that demonstrate the required sensitivity shall be considered valid for interpretation. When multiple IQIs are used to cover different thickness ranges, the contrast and brightness range that demonstrates the required image of each IQI shall be determined. Intervening thicknesses may be interpreted using the overlapping portions of the determined contrast and brightness ranges. When there is no overlap, additional IQIs shall be used. The SPIP or DDA shall be calibrated for sensitivity by the operator using the "standard" built into the software and an ASTM IQI per the standardized written procedure.

8.10.12 Identification Marks. An image identification mark and two location identification marks shall be placed on the steel at each radiograph or imaging location. A corresponding radiograph identification mark and two location identification marks, all of which shall show in the image, shall be produced by placing lead numbers or letters, or both, over each of the identical identification and location marks made on the steel to provide a means for matching the image to the weld or base metal. Additional identification information may be preprinted no less than 20 mm [3/4 in] from the edge of the weld or shall be produced on the radiographic film or digital image by placing lead figures on the steel.

Information shown on the radiographic film or digital image shall include the Owner's contract identification, initials of the radiographic inspection company, initials of the fabricator, the fabricator's shop order number, the radiographic identification (erection) mark, the date, and the weld repair number, if applicable. For digital images, the additional information may be added as text on the processed image. When such text information is added, the software locking tool shall be enabled to prevent subsequent editing of the information.

8.10.13 Linear Reference Comparators. When using SPIPs or DDAs, a measuring scale or an object of known dimension shall be used to serve as a linear reference comparator. The comparator shall be attached to the SPIP holder or DDA prior to exposure. As an alternative, when using SPIPs a transparent scale with opaque gradations may be placed on the SPIP prior to processing. In any case, the reference comparator shall not interfere with interpretation of the image.

8.10.14 Edge Blocks. Edge blocks shall be used when radiographing welds in butt joints greater than 12 mm [1/2 in] in thickness. The edge blocks shall have a length sufficient to extend beyond each side of the weld center-line for a minimum distance equal to the weld thickness, but no less than 50 mm [2 in], and shall have a thickness equal to or greater than the thickness of the weld. The minimum width of the edge blocks shall be equal to half the weld thickness, but no less than 25 mm [1 in]. The edge blocks shall be centered on the weld with a snug fit against the plate being radiographed, allowing no more than a 3 mm [1/8 in] gap. Edge blocks shall be made of radiographically clean steel and the surface shall have a finish of ANSI 3 µm [125 µin] or smoother. See Figure 8.2.

8.11 Acceptability of Welds

Welds shown by RT to have discontinuities unacceptable per 8.26.2 shall be corrected in conformance with 5.7.

8.12 Examination, Report, and Disposition of Radiographs

8.12.1 Equipment Provided by Contractor.

8.12.1.1 Film Radiography. The Contractor shall provide a suitable variable intensity illuminator (viewer) with spot review or masked spot-review capability. The viewer shall incorporate a means for adjusting the size of the spot under examination. The viewer shall have sufficient capacity to properly illuminate radiographs with an H & D density of 4.0. Film review shall be done in an area of subdued light.

8.12.1.2 Digital Radiography. The Contractor shall provide a suitable workstation monitor for evaluating images. The workstation monitor shall have a display resolution with a pixel count which is equal to or greater than the pixel count of the DDA or SPIP. Image review shall be performed in an area of subdued light and away from background glare.

8.12.2 Reports. Before a weld subject to RT is accepted, all of its radiographic film and digital images, including any showing defects prior to repair and those showing acceptable final quality, shall be submitted to the QA Inspector for review and acceptance. The radiographic film or digital images shall be accompanied by the report interpreting the results and signed by the Contractor's RT technician.

8.12.3 Radiographic Film or Digital Image Retention. A full set of radiographic film and digital images for welds subject to RT as described in 8.12.2 shall be delivered to the Owner on completion of the work. The Contractor's obligation to retain radiographic film and digital images shall cease:

(1) upon delivery of this full set to the Owner, or

(2) one full year after the completion of the Contractor's work, provided the Owner has declined to accept the radiographs.

8.12.4 Radiographic Film or Digital Image Archival

8.12.4.1 Radiographic Film. Radiographic film shall be stored in accordance with ASTM E1254, *Standard Guide for Storage of Radiographs and Unexposed Industrial Radiographic Films*.

8.12.4.2 Radiographic Digital Images. Radiographic digital images shall be archived using a reproducible electronic medium. Data file format shall comply with ASTM E2699, *Standard Practice for Digital Imaging and Communication in Nondestructive Evaluation (DICONDE) for Digital Radiographic (DR) Test Methods*. The image archival method shall be documented and proven at system installation. This shall include the image file nomenclature to enable the retrieval of images at a later date. Archived image files shall maintain the bit depth and spatial resolution of the original image. Image data compression shall not be allowed. The initial image presented by the SPIP or DDA system shall be preserved (stored) without altering the original spatial resolution and pixel intensity. The final image used for disposition shall also be archived when additional image processing is applied (excluding window/level and digital image zoom) to achieve the required image quality level. Annotations made to the image shall be stored in a manner which will not mask or hide diagnostic areas of the image.

Part C
Ultrasonic Testing (UT) of Groove Welds

8.13 General

8.13.1 The procedures and standards set forth in Part C govern the UT of groove welds and HAZ between the thicknesses of 8 mm and 200 mm [5/16 in and 8 in] inclusive, when such testing shall be required by 8.7.

8.13.2 Variations in testing procedure, equipment, and acceptance standards not included in Part C of Clause 8 may be used upon agreement with the Engineer. Such variations include other thicknesses, weld geometries, transducer sizes, frequencies, couplant, coated surfaces, testing techniques, etc. Such approved variations shall be recorded in the contract records.

8.13.3 To detect possible piping porosity, RT is required to supplement UT of ESW and EGW.

8.13.4 These procedures are not intended to be employed for the procurement testing of base metals. However, welding-related discontinuities (cracking, lamellar tearing, delaminations, etc.) in the adjacent base metal, which would not be acceptable under the provisions of this code, shall be reported to the Engineer for disposition.

8.14 Extent of Testing

8.14.1 The provisions of 8.7 shall identify the minimum extent of UT.

8.14.2 The UT operator shall, prior to making a UT examination, be furnished or have access to relevant information regarding weld-joint geometry, material thickness, and welding processes used in making the weldment. Any subsequent record of repairs made to the weldment shall also be made available to the UT operator.

8.15 UT Equipment

8.15.1 The UT instrument shall be the pulse-echo type suitable for use with transducers oscillating at frequencies between 1 megahertz (MHz) and 6 MHz. The display shall be an "A" scan rectified video trace.

8.15.2 The horizontal linearity of the test instrument shall be qualified over the full sound-path distance to be used in testing in conformance with 8.22.1 (see 8.17.1).

8.15.3 Test instruments shall be internally stabilized so that after warm-up, no variation in response greater than 1 dB occurs with a supply voltage change of 15% nominal or, in the case of a battery, within the charge operating life. There shall be an alarm or meter to signal a drop in battery voltage prior to instrument shutoff due to battery exhaustion.

8.15.4 The test instrument shall have a calibrated gain control (attenuator) adjustable in discrete 1 dB or 2 dB steps over a range of at least 60 dB. The accuracy of the gain control (attenuator) settings shall be within plus or minus 1 dB. The procedure for qualification shall be as described in 8.17.2 and 8.22.2.

8.15.5 The dynamic range of the instrument's display shall be such that a difference of 1 dB of amplitude can be easily detected on the display.

8.15.6 Straight beam (longitudinal wave) search unit transducers shall have an active area of not less than 300 square millimeters [1/2 square inch] nor more than 650 square millimeters [1 square inch]. The transducer shall be round or square. Transducer frequency shall be 2 MHz to 2.5 MHz. Transducers shall be capable of resolving the three reflections as described in 8.21.1.3.

8.15.7 Angle-beam search units shall consist of a transducer and an angle wedge. The unit may be comprised of the two separate elements or may be an integral unit.

8.15.7.1 The transducer frequency shall be between 2 MHz and 2.5 MHz, inclusive.

8.15.7.2 The transducer crystal shall be square or rectangular in shape and may vary from 15 mm to 25 mm [5/8 in to 1 in] in width and from 15 mm to 20 mm [5/8 in to 3/4 in] in height (see Figure 8.3). The maximum ratio of width to height shall be 1.2 to 1.0, and the minimum ratio 1.0 to 1.0.

8.15.7.3 The search unit shall produce a sound beam in the material being tested within plus or minus 2° of one of the following proper angles: 70°, 60°, or 45°, as described in 8.21.2.2.

8.15.7.4 Each search unit shall be marked to clearly indicate the frequency of the transducer, nominal angle of refraction, and index point. The index point location procedure is described in 8.21.2.1.

8.15.7.5 Maximum allowable internal reflections from the search unit shall be as described in 8.17.3.

8.15.7.6 The dimensions of the search unit shall be such that the distance from the leading edge of the search unit to the index point shall not exceed 25 mm [1 in] (see Figure 8.4).

8.16 Reference Standards

8.16.1 The International Institute of Welding (IIW) ultrasonic reference block, shown in Figure 8.5A, shall be the standard used for both distance and sensitivity calibration. Other portable blocks may be used, provided the reference level sensitivity for the instrument/search unit combination is adjusted to be equivalent to that achieved with the IIW Block (see Annex E, Part A, for examples). Other approved designs are shown in Figure 8.5B.

8.16.2 The use of a "corner" reflector for calibration purposes shall be prohibited.

8.16.3 The combination of search unit and instrument shall resolve three holes in the RC resolution reference test block shown in Figure 8.5B. The search unit position shall be as described in 8.21.2.5. The resolution shall be evaluated with the instrument controls set at normal test settings and with indications from the holes brought to mid-screen height. Resolution shall be sufficient to distinguish at least the peaks of indications from the three holes.

8.17 Equipment Qualification

8.17.1 The horizontal linearity of the test instrument shall be prequalified after each two months of instrument use in each of the distance ranges over which the instrument will be used. The qualification procedure shall be in conformance with 8.22.1 (see Annex E, E3 for alternative method).

8.17.2 The instrument's gain control (attenuator) shall meet the requirements of 8.15.4 and shall be checked for correct calibration at periods not to exceed two month intervals in conformance with 8.22.2. Alternative methods may be used for calibrated gain control (attenuator) qualification if proven at least equivalent with 8.22.2.

8.17.3 Maximum internal reflections from each search unit shall be verified at a maximum time interval of 40 hours of instrument use, in conformance with 8.22.3.

8.17.4 With the use of an approved calibration block, each angle-beam search unit shall be checked after each eight hours of use to determine that the contact face is flat, that the sound entry point is correct, and that the beam angle is within the allowed plus or minus 2° tolerance in conformance with 8.21.2.1 and 8.21.2.2. Search units that do not meet these requirements shall be corrected or replaced.

8.18 Calibration for Testing

8.18.1 All calibrations and tests shall be made with the reject (clipping or suppression) control turned off. Use of the reject (clipping or suppression) control may alter the amplitude linearity of the instrument and invalidate test results.

8.18.2 Calibration for sensitivity and horizontal sweep (distance) shall be made by the UT operator just prior to testing and at the location of each weld.

8.18.3 Recalibration shall be made after a change of operators, after each two-hour maximum time interval, or when the electrical circuitry is disturbed in any way, which includes the following:

(1) Transducer change

(2) Battery change

(3) Electrical outlet change

(4) Coaxial cable change

(5) Power outage (failure)

8.18.4 Calibration for straight-beam testing of base metal shall be made with the search unit applied to Face A of the base metal and performed as follows:

8.18.4.1 The horizontal sweep shall be adjusted for distance calibration to present the equivalent of at least two plate thicknesses on the display.

8.18.4.2 The sensitivity shall be adjusted at a location free of indications so that the first back reflection from the far side of the plate will be 50% to 75% of full screen height.

8.18.5 Calibration for angle-beam testing shall be performed as follows (see Annex E, E2.4 for alternative method):

8.18.5.1 The horizontal sweep shall be adjusted to represent the actual sound path distance by using the IIW block or alternative blocks as specified in 8.16.1. The distance calibration shall be made using either the 125 mm [5 in] scale or 250 mm [10 in] scale on the CRT screen, whichever is appropriate, unless joint configuration or thickness prevents full examination of the weld at either of these settings, in which case, the distance calibration shall be made using 400 mm [15 in] or 500 mm [20 in] scale as required. The search unit position is described in 8.21.2.3. At least two indications other than the initial pulse shall also be used for this distance calibration, because of the built-in time delay between the transducer face and the face of the search unit.

8.18.5.2 **Zero Reference Level.** The zero reference level sensitivity used for discontinuity evaluation ("b" on the ultrasonic test report, Annex E, Form E–4) is attained by adjusting the calibrated gain control (attenuator) of the test instrument, meeting the requirements of 8.15, so that a maximized horizontal trace deflection [adjusted to horizontal reference line height with calibrated gain control (attenuator)] results on the display at 40% to 60% screen height, in conformance with 8.21.2.4.

See Annex E, Part B, Form E–4 for a sample UT report form.

8.19 Testing Procedures

8.19.1 An "X" line for discontinuity location shall be marked on the test face of the weldment in a direction parallel to the weld axis. The location distance perpendicular to the weld axis is based on the dimensional figures on the detail drawing and usually falls on the centerline of butt joint welds. It always falls on the near face of the connecting member of T and corner joint welds (the face opposite Face C).

8.19.2 A "Y" accompanied with a weld identification number shall be clearly marked on the base metal adjacent to each weld that is ultrasonically tested. This marking is used for the following purposes:

(1) Weld identification

(2) Identification of Face A

(3) Distance measurements and direction (+ or –) from the X line

(4) Location measurement from weld ends or edges

8.19.3 All surfaces to which a search unit is applied shall be free of weld spatter, dirt, grease, oil (other than that used as a couplant), coatings, and loose scale and shall have a contour allowing intimate coupling.

8.19.4 A couplant material shall be used between the search unit and the test material. The couplant shall be either glycerin or a cellulose gum and water mixture of a suitable consistency. A wetting agent may be added if needed. Light machine oil may be used for couplant on calibration blocks.

8.19.5 The entire base metal through which ultrasound must travel to test the weld shall be tested for laminar reflectors using a straight beam search unit conforming to the requirements of 8.15.6 and calibrated in conformance with 8.18.4. If any area of base metal exhibits total loss of back reflection or an indication equal to or greater than the original back reflection height is located in a position that will interfere with the normal weld scanning procedure, its size, location, and depth from Face A shall be determined and reported on the UT report, and an alternate weld scanning procedure shall be used.

8.19.5.1 The reflector size evaluation procedure shall be in conformance with 8.23.1.

8.19.5.2 If part of a weld is inaccessible to testing in conformance with the requirements of Table 8.3, due to laminar content recorded in conformance with 8.19.5, the testing shall be conducted using one or more of the following alternative procedures as necessary to attain full weld coverage:

(1) Grind the weld surface(s) flush.

(2) Test from Faces A and B.

(3) Use other search unit angles.

8.19.6 Welds shall be tested using an angle-beam search unit conforming to the requirements of 8.15.7 with the instrument calibrated in conformance with 8.18.5 using the angles shown in Table 8.3. Following calibration and during testing, the only instrument adjustment allowed is the sensitivity-level adjustment with the calibrated gain control (attenuator). The reject (clipping or suppression) control shall be turned off. Sensitivity shall be increased from the reference level for weld scanning in conformance with the provisions of Tables 8.4 or 8.5, as applicable.

8.19.6.1 The testing angle and scanning procedure shall be in conformance with those shown in Table 8.3.

8.19.6.2 All butt joint welds shall be tested from each side of the weld axis. Corner and T-joint welds shall be primarily tested from one side of the weld axis only. All welds shall be tested using the applicable scanning pattern or patterns shown in Figure 8.7 as necessary to detect both longitudinal and transverse discontinuities. It is intended that, as a minimum, all welds be tested by passing sound through the entire volume of the weld and the HAZ in two crossing directions, wherever practical.

8.19.6.3 When a discontinuity indication appears on the screen, the maximum attainable indication from the discontinuity shall be adjusted to produce a horizontal reference level trace deflection on the display. This adjustment shall be made with the calibrated gain control or (attenuator), and the instrument reading in decibels shall be used as the "Indication Level," "a," for calculating the "Indication Rating," "d," as shown on the test report (Annex E, Part B, Form E–4).

8.19.6.4 The "Attenuation Factor," "c," on the test report shall be attained by subtracting 25 mm [1 in] from the sound path distance and multiplying the remainder by 2 for U.S. Customary Units or by 0.08 for SI Units. This factor shall be rounded out to the nearest dB value. Fractional values less than 1/2 dB shall be reduced to the lower dB level and those of 1/2 or greater increased to the higher level.

8.19.6.5 The "Indication Rating," "d," in the UT Report, Annex E, Part B, Form E–4, represents the algebraic difference in decibels between the indication level and the reference level with correction for attenuation as indicated in the following expressions:

Instruments with gain in dB: a – b – c = d

Instruments with attenuation in dB: b – a – c = d

8.19.7 The length of discontinuities shall be determined in conformance with the procedure in 8.23.2.

8.19.8 Each weld discontinuity shall be accepted or rejected on the basis of its indication rating and its length in conformance with Tables 8.4 or 8.5. Only those discontinuities that are rejectable need be recorded on the test report, except that for welds designated in the contract documents as being Fracture Critical, indication ratings that are up to and including 6 dB less critical (higher) than acceptance levels shall be recorded on the test report.

8.19.9 Each rejectable discontinuity shall be indicated on the weld by a mark directly over the discontinuity for its entire length. The depth from the surface and indication rating shall be noted on nearby base metal.

8.19.9.1 Evaluation of retested areas of repaired welds shall be tabulated on a new line on the report form. If the original form is used, an R1, R2, etc., shall prefix the indication number, designating the number of repairs having been made in that specific area.

8.19.9.2 If additional report forms are used, the R number shall prefix the report number.

8.19.10 Welds found unacceptable by UT shall be repaired by the methods described in 5.7. Repaired areas shall be retested ultrasonically, with results tabulated on the original form (if available) or additional report forms.

8.20 Preparation and Disposition of Reports

8.20.1 A report form that clearly identifies the work and the area of inspection shall be completed by the UT technician at the time of inspection. The report form for welds that are acceptable need only contain sufficient information to identify the weld, the Inspector (signature), and the acceptability of the weld. An example of such a form is shown in Annex E, Part B, Form E–4.

8.20.2 Before a weld subject to UT is accepted, all report forms pertaining to the weld, including any indentifying defects prior to repair and those signifying acceptable final quality, shall be submitted to the QA Inspector for review and acceptance. The reports shall be signed by the Contractor's UT technician.

8.20.3 A full set of completed report forms of welds subject to UT, including any that show unacceptable quality prior to repair, shall be delivered to the Owner on completion of the work. The Contractor's obligation to retain UT reports shall cease (1) upon delivery of this full set to the Owner or (2) one full year after completion of the Contractor's work, provided that the Owner is given prior written notice.

8.21 Calibration of the UT Unit With IIW or Other Approved Reference Blocks

See 8.16 and Figures 8.5A, 8.5B, and 8.6.

8.21.1 Longitudinal Mode

8.21.1.1 The distance calibration procedure shall be as follows: (see Annex E, E1 for alternative method):

(1) Set the transducer in position G on the IIW block.

(2) Adjust instrument to produce indications at 25 mm [1 in], 50 mm [2 in], 75 mm [3 in], 100 mm [4 in], etc., on the display.

8.21.1.2 The amplitude procedure shall be as follows (see Annex E, E1.2 for alternative method):

(1) Set the transducer in position G on the IIW block.

(2) Adjust the gain until the maximized indication from first back reflection attains 50% to 75% screen height.

8.21.1.3 The resolution procedure shall be as follows:

(1) Set the transducer in position F on the IIW block.

(2) Transducer and instrument should resolve all three distances.

8.21.1.4 Horizontal linearity qualification procedures shall be in conformance with 8.17.1.

8.21.1.5 The gain control (attenuator) qualification shall be as follows:

(1) Set the transducer in position T on DS block.

(2) Move the transducer toward position U per instructions in 8.17.2.

8.21.2 Shear Wave Mode (Transverse)

8.21.2.1 Locate or check the transducer sound entry point (index point) by the following procedure:

(1) Set the transducer in position D on the IIW block.

(2) Move the transducer until the signal from the radius is maximized. The point on the transducer that aligns with the radius line on the calibration block is the point of sound entry (see Annex E, E2.1 for alternative method).

8.21.2.2 Check or determine the transducer sound-path angle by one of the following procedures:

(1) Set the transducer in position B on IIW block for angles 40° through 60°, or in position C on IIW block for angles 60° through 70° (see Figure 8.6).

(2) For the selected angle, move the transducer back and forth over the line indicative of the transducer angle until the signal from the radius is maximized. Compare the sound entry point on the transducer with the angle mark on the calibration block (tolerance ±2°) (see Annex E, EA2.2 for alternative methods).

8.21.2.3 The distance calibration procedure shall be as follows:

(1) Set the transducer in position D on the IIW block (any angle).

(2) Adjust the instrument to attain indications at 100 mm [4 in] and 200 mm [8 in] or 225 mm [9 in] on the display; 100 mm [4 in] and 225 mm [9 in] on Type 1 block; or 100 mm [4 in] and 200 mm [8 in] on a Type 2 block (see Annex E for alternate methods using the DSC or DC block).

8.21.2.4 The amplitude or sensitivity calibration procedure shall be as follows:

(1) Set the transducer in position A on the IIW block (any angle);

(2) Adjust the maximized signal from the 1.5 mm [0.06 in] hole to attain a horizontal reference-line height indication (see Annex E, E2.4 for alternative method).

(3) The maximum decibel reading obtained shall be used as the "Reference Level," "b" reading on the Test Report sheet (Annex E, Part B, Form E–4) per 8.16.1.

8.21.2.5 The resolution procedure is as follows:

(1) Set the transducer on resolution block RC position Q for 70° angle, position R for 60° angle, or position S for 45° angle.

(2) Resolve the three test holes, at least to the extent of distinguishing the peaks of the indications from the three holes, by the transducer and instrument.

8.22 Equipment Qualification Procedures

8.22.1 Horizontal Linearity Procedure. The following procedure shall be used for instrument qualification (see Annex E, E3, for alternative method).

(1) Couple a straight-beam search unit meeting the requirements of 8.15.6 to the IIW or DS block in Position G, T, or U (see Figure 8.6) as necessary to attain 5 back reflections in the qualification range being certified (see Figure 8.6).

(2) Adjust the first and fifth back reflections to their proper locations with use of the distance calibration and zero delay adjustments.

(3) Each indication shall be adjusted to reference level with the gain or attenuation control for horizontal-location examination.

(4) Each intermediate trace deflection location shall be correct within ±2% of the screen width.

8.22.2 Decibel dB Accuracy Procedure. In order to attain the accuracy (±1%) in reading the indication height, the display must be graduated vertically at 2% intervals or 2.5% for instruments with digital amplitude readout at horizontal midscreen height. These graduations shall be placed on the display between 60% and 100% of screen height. This may be accomplished with use of a graduated transparent screen overlay. If this overlay is applied as a permanent part of the UT unit, care should be taken that the overlay does not obscure normal testing displays.

(1) Couple a straight-beam search unit, meeting the requirements of 8.15.6, to the DS block shown in Figure 8.5B and position "T," Figure 8.6.

(2) Adjust the distance calibration so that the first 50 mm [2 in] back reflection indication (hereafter called "the indication") is at horizontal midscreen.

(3) Adjust the calibrated gain or attenuation control so that the indication is exactly at or slightly above 40% screen height.

(4) Move the search unit toward position U (see Figure 8.6), until the indication is at exactly 40% screen height.

(5) Increase the sound amplitude 6 dB with the calibrated gain or attenuation control. The indication level theoretically should be exactly at 80% screen height.

(6) Record the dB reading under "a" and actual percent screen height under "b" from step 5 on the certification report (Annex E, Part B, Form E–1), line 1.

(7) Move the search unit further toward position U, Figure 8.6, until the indication is at exactly 40% screen height.

(8) Repeat step 5.

(9) Repeat step 6; except, information should be applied to the next consecutive line on Annex E, Part B, Form E–1.

(10) Repeat steps 7, 8, and 9 consecutively until the full range of the gain control (attenuator) is reached (60 dB minimum).

(11) Apply the information from columns "a" and "b" to equation 8.22.2.1 or the nomograph described in 8.22.2.3 to calculate the corrected dB.

(12) Apply corrected dB from step 11 to column "c."

(13) Subtract Column "c" value from Column "a" value and apply the difference in Column "d," dB error.

(14) Information shall be tabulated on a form, including minimum equivalent information as displayed on Form E–1, and the unit evaluated in conformance with instructions shown on that form. These values may be either positive or negative and shall be so noted.

(15) Form E–2 provides a relatively simple means of evaluating data from item.

(16) Instructions for this evaluation are given in (17) through (19).

(17) Apply the dB information from column "e" (Form E–1) vertically and dB reading from column "a" (Form E–1) horizontally as X and Y coordinates for plotting a dB curve on Form E–2.

(18) The longest horizontal length, as represented by the dB reading difference, which can be inscribed in a rectangle representing 2 dB in height, denotes the dB range in which the equipment meets the code requirements. The minimum allowable range shall be 60 dB.

(19) Equipment that does not meet this minimum requirement may be used, provided correction factors are developed and used for discontinuity evaluation outside the instrument acceptable linearity range, or the weld testing and discontinuity evaluation are kept within the acceptable vertical linearity range of the equipment. The dB error figures (Column "d") may be used as correction factor figures.

8.22.2.1 The decibel calculating equation is as follows:

(1) $dB_2 - dB_1 = 20 \times \text{Log}(\%_2 / \%_1)$

or

$dB_2 = 20 \times \text{Log}(\%_2 / \%_1) + dB_1$

(2) As related to Annex E, Part B, Form E–1:

dB_1 = Column a

dB_2 = Column c

$\%_1$ = Column b

$\%_2$ = Defined on Form E–1

8.22.2.2 For notes on the use of the nomograph, see Annex E, Part B, Form E–3:

(1) Columns a, b, c, d, and e are on certification sheet, Annex E, Part B, Form E–1.

(2) The A, B, and C scales are on the nomograph, Annex E, Part B, Form E–3.

(3) The zero points on the C scale shall be prefixed by adding the necessary value to correspond with the instrument settings, i.e., 0, 10, 20, 30, etc.

8.22.2.3 Procedures for using the nomograph shall be as follows:

(1) Extend a straight line between the decibel reading from Column "a" applied to the C scale and the corresponding percentage from Column "b" applied to the A scale.

(2) Use the point where the straight line from step 1 crosses the pivot line B as a pivot point for a second straight line.

(3) Extend a second straight line from the average percentage point on the A scale through the pivot point developed in step 2 and on to the dB scale C.

(4) This point on the C scale is indicative of the corrected dB for use in Column "c."

8.22.2.4 For an example of the use of the nomograph, see Annex E, Part B, Form E–3.

8.22.3 Procedure for internal reflections shall be as follows:

(1) Calibrate the equipment in conformance with 8.18.5.

(2) Remove the search unit from the calibration block without changing any other equipment adjustments.

(3) Increase the calibrated gain or attenuation 20 dB more sensitive than reference level.

(4) The screen area beyond 12 mm [1/2 in] sound path and above reference level height shall be free of any indication.

8.23 Discontinuity Size Evaluation Procedures

8.23.1 Straight (Longitudinal) Beam Testing. The size of lamellar discontinuities will not always be easily determined, especially those that are smaller than the transducer size. When the discontinuity is larger than the transducer, a full loss of back reflection will occur and a 6 dB loss of amplitude and measurement to the centerline of the transducer is usually reliable for determining discontinuity edges. However, the approximate size evaluation of those reflectors, which are smaller than the transducer, shall be made by beginning outside of the discontinuity with equipment calibrated in conformance with 8.18.4 and moving the transducer toward the area of discontinuity until an indication on the screen begins to form. The leading edge of the search unit at this point is indicative of the edge of the discontinuity.

8.23.2 Angle-Beam (Shear) Testing. The following procedure shall be used to determine the lengths of discontinuities which have indication ratings more serious than for a Class D discontinuity. The length of such discontinuities shall be determined by measuring the distance between the transducer centerline locations where the indication rating drops 50%

(6 dB) below the rating for the applicable discontinuity classification. This length shall be recorded under "discontinuity length" on the test report. When warranted by indication amplitude, this procedure shall be repeated to determine the length of Class A, B, and C discontinuities.

8.24 Scanning Patterns

See Figure 8.7.

8.24.1 Longitudinal Discontinuities

8.24.1.1 Scanning Movement A. Rotation angle a = 10°.

8.24.1.2 Scanning Movement B. Scanning distance b shall be such that the section of weld being tested is covered.

8.24.1.3 Scanning Movement C. Progression distance c shall be approximately one-half the transducer width. Movements A, B, and C shall be combined into one scanning pattern.

8.24.2 Transverse Discontinuities

8.24.2.1 Use scanning pattern D (when welds are finished flush).

8.24.2.2 Use scanning pattern E (when weld reinforcement is not finished flush); Scanning angle e = 15° max. The scanning pattern shall be such that the full weld section is covered.

8.24.3 Additional Scanning Pattern for ESW or EGW Welds. For ESW and EGW, in addition to other scanning patterns required, scanning pattern E shall be used with search unit rotation angle e between 45° and 60°. The scanning pattern shall be such that the full weld section is covered.

8.25 Examples of dB Accuracy Certification

Annex E, Part B, shows examples of the use of Forms E-1, E-2, and E-3 for the solution to a typical application of 8.22.2.

Part D
Weld Acceptance Criteria

8.26 Quality of Welds

8.26.1 Visual Inspection. All welds shall be visually inspected. A weld shall be acceptable by visual inspection if it conforms to the following requirements:

8.26.1.1 Cracks. The weld shall have no cracks.

8.26.1.2 Fusion. Thorough fusion shall exist between adjacent layers of weld metal and between weld metal and base metal.

8.26.1.3 Craters. All craters are to be filled to the full cross section of the weld, except for the ends of intermittent fillet welds outside of their effective length when such welds are allowed in the design.

8.26.1.4 Profile. Weld profiles shall be in conformance with 5.6.

8.26.1.5 Undercut Allowance. Except when weld reinforcement is required to be removed, undercut limits shall be as follows:

(1) Undercut in main members, undercut shall be no more than 0.25 mm [0.01 in] deep when the weld is transverse to tensile stress under any design loading condition.

(2) Undercut in all other cases shall be no more than 1 mm [1/32 in] deep for all other cases.

8.26.1.6 Piping Porosity. The frequency of piping porosity in the surface of fillet welds shall not exceed one in 100 mm [4 in] or six in 1200 mm [4 ft] of weld length and the maximum diameter shall not exceed 2.4 mm [3/32 in].

(1) A subsurface inspection for porosity shall be performed whenever piping porosity 2.4 mm [3/32 in] or larger in diameter extends to the surface at intervals of 300 mm [12 in] or less over a distance of 1200 mm [4 ft], or when the

condition of electrodes, flux, base metal, or the presence of weld cracking indicates that there may be a problem with piping or gross porosity.

(2) This subsurface inspection shall be a visual inspection of 300 mm [12 in] exposed lengths of the fillet weld throat after it has been removed to 1/2 the design throat by carbon arc gouging or grinding. When viewed at mid-throat of the weld, the sum of the diameters of all porosity shall not exceed 10 mm [3/8 in] in any 25 mm [1 in] length of weld or 20 mm [3/4 in] in any 300 mm [12 in] length of weld.

8.26.1.7 Underrun. A fillet weld in any single continuous weld may underrun the nominal fillet weld size specified by 2 mm [1/16 in] without correction, provided that the undersize portion of the weld does not exceed 10% of the length of the weld. On the web-to-flange welds on girders, underrun shall be prohibited at the ends for a length equal to twice the width of the flange.

8.26.1.8 Piping Porosity in CJP Tension Joints. CJP groove welds in butt joints transverse to the direction of computed tensile stress shall have no piping porosity. For all other groove welds, the frequency of piping porosity shall not exceed one in 100 mm [4 in] of length, and the maximum diameter shall not exceed 2.4 mm [3/32 in].

8.26.1.9 Time of Inspection. Visual inspection of welds in all steels may begin immediately after the completed welds have cooled to ambient temperature. Acceptance criteria for M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W] steel shall be based on visual inspection performed not less than 48 hours after completion of the weld.

8.26.2 Radiographic (RT) and Magnetic Particle (MT) Inspection. Welds that are subject to RT or MT in addition to visual inspection shall have no cracks and shall be unacceptable if the RT or MT shows any of the types of discontinuities described in 8.26.2.1, 8.26.2.2, 8.26.2.3, or 8.26.2.4.

8.26.2.1 Welds Carrying Tensile Stress. For welds subject to tensile stress under any condition of loading, the greatest dimension of any porosity or fusion-type discontinuity that is 2 mm [1/16 in] or larger in greatest dimension shall not exceed the size, B, indicated in Figure 8.8 for the effective throat or weld size involved. The distance from any porosity or fusion-type discontinuity described above to another such discontinuity, to an edge, or to the toe or root of any intersecting flange-to-web weld shall be not less than the minimum clearance allowed, C, indicated in Figure 8.8 for the size of discontinuity under examination.

8.26.2.2 Welds Carrying Compressive Stress. For welds subject only to compressive or shear stress, the greatest dimension of porosity or a fusion-type discontinuity that is 3 mm [1/8 in] or larger in greatest dimension shall not exceed the size, B, nor shall the space between adjacent discontinuities be less than the minimum clearance allowed, C, indicated by Figure 8.9 for the size of discontinuity under examination.

8.26.2.3 Discontinuities Less Than 1.6 mm [1/16 in] Independent of the requirements of 8.26.2.1 and 8.26.2.2, discontinuities having a greatest dimension of less than 2 mm [1/16 in] shall be unacceptable if the sum of their greatest dimensions exceeds 10 mm [3/8 in] in any 25 mm [1 in] length of weld.

8.26.2.4 Limitations. The limitations given by Figures 8.8 and 8.9 for 38 mm [1-1/2 in] weld size shall apply to all weld sizes greater than 38 mm [1-1/2 in].

8.26.2.5 Annex K Illustration. Annex K illustrates the application of the requirements given in 8.26.2.1.

8.26.3 UT

8.26.3.1 Acceptance Criteria. Welds that are subject to UT in addition to visual inspection shall be acceptable if they meet the following requirements:

(1) Welds subject to tensile stress under any condition of loading shall conform to the requirements of Table 8.4.

(2) Welds subject to compressive stress shall conform to the requirements of Table 8.5.

8.26.3.2 Indications. Ultrasonically tested welds are evaluated on the basis of a discontinuity reflecting ultrasound in proportion to its effect on the integrity of the weld.

(1) Indications of discontinuities that remain on the screen as the search unit is moved towards and away from the discontinuity (scanning movement "b") may be indicative of planar discontinuities with significant through-thickness height.

(2) As the orientation of such discontinuities, relative to the sound beam, deviates from the perpendicular, indication ratings may result that do not allow, reliable evaluation of the welded joint integrity.

(3) When indications that exhibit these planar characteristics are present at scanning sensitivity, a more detailed evaluation of the discontinuity by other means may be required (e.g., alternate UT techniques, RT, grinding, or gouging for visual inspection, etc.).

8.26.3.3 Scanning. CJP groove web-to-flange welds shall conform to the requirements of Table 8.5, and acceptance for discontinuities detected by scanning movements other than scanning pattern "E" (see 8.24.2.2) may be based on a weld thickness equal to the actual web thickness plus 25 mm [1 in].

(1) Discontinuities detected by scanning pattern E shall be evaluated to the criteria of 8.26.3.1 for the actual web thickness.

(2) When such web-to-flange welds are subject to calculated tensile stress normal to the weld axis, they shall be so designated on design drawings and shall conform to the requirements of Table 8.4.

8.26.4 Liquid Penetrant Inspection. Welds that are subject to PT, in addition to visual inspection, shall be evaluated on the basis of the requirements for visual inspection.

8.26.5 Timing of NDT

8.26.5.1 Timing of Testing. When welds are subject to NDT in conformance with 8.26.2, 8.26.3, and 8.26.4, the testing may begin immediately after the completed welds have cooled to ambient temperature.

8.26.5.2 Grade HPS 690W [HPS 100W] Steel. Acceptance of welds in M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W] steel shall be based on NDT performed not less than 48 hours after completion of the welds.

Table 8.1
NDT Methods and Frequency

<table>
<tr><th>Weld Type</th><th>Joint Type</th><th>Process</th><th>Member Design Stress Type</th><th>NDT Method</th><th>Frequency</th></tr>
<tr><td rowspan="13">CJP groove welds</td><td rowspan="4">Butt joints other than in webs of flexural members</td><td rowspan="2">Other than ESW or EGW</td><td>Tension or reversal</td><td>RT</td><td>100% of each joint</td></tr>
<tr><td>Compression or shear</td><td>UT or RT</td><td>25% (See 8.7.4)</td></tr>
<tr><td rowspan="2">ESW or EGW</td><td>Tension or reversal</td><td rowspan="2">RT and UT</td><td>100% of each joint</td></tr>
<tr><td>Compression or shear</td><td>25% (See 8.7.4)</td></tr>
<tr><td rowspan="4">Butt joints in webs of flexural members, transverse to the direction of bending stress</td><td>Other than ESW or EGW</td><td rowspan="2">Tension</td><td>RT</td><td rowspan="2">1/6 of the web depth beginning at the tension flange or flanges for each joint</td></tr>
<tr><td>ESW or EGW</td><td>RT and UT</td></tr>
<tr><td>Other than ESW or EGW</td><td rowspan="2">Compression</td><td>UT or RT</td><td rowspan="2">25% of the remainder of the web depth for each joint</td></tr>
<tr><td>ESW or EGW</td><td>RT and UT</td></tr>
<tr><td rowspan="2">Butt joints in webs of flexural members, parallel to the direction of bending stress</td><td>Other than ESW or EGW</td><td rowspan="2">Shear</td><td>UT or RT</td><td rowspan="2">25% (See 8.7.4)</td></tr>
<tr><td>ESW or EGW</td><td>RT and UT</td></tr>
<tr><td rowspan="2">T- or corner joints</td><td rowspan="2">Any</td><td>Tension or reversal</td><td rowspan="2">UT</td><td>100% of each joint</td></tr>
<tr><td>Compression or shear (including web to either flange)</td><td>25% (See 8.7.4)</td></tr>
<tr></tr>
<tr><td>PJP groove welds and fillet welds, Grade HPS 690W [HPS 100W]</td><td rowspan="2">Any</td><td rowspan="2">Any</td><td rowspan="2">Any</td><td rowspan="2">MT</td><td>100% of each joint</td></tr>
<tr><td>PJP groove welds and fillet welds, all other grades</td><td>10% (See 8.7.4)</td></tr>
</table>

Table 8.2A
Hole-Type IQI Requirements (see 8.10.7)

Nominal Material Thickness Range, mm [in]	Source Side	
	Designation	Essential Hole
Up to 6 [1/4] incl.	10	4T
Over 6 to 10 [1/4 to 3/8]	12	4T
Over 10 to 12 [3/8 to 1/2]	15	4T
Over 12 to 16 [1/2 to 5/8]	15	4T
Over 16 to 20 [5/8 to 3/4]	17	4T
Over 20 to 22 [3/4 to 7/8]	20	4T
Over 22 to 25 [7/8 to 1]	20	4T
Over 25 to 32 [1 to 1-1/4]	25	4T
Over 32 to 38 [1-1/4 to 1-1/2]	30	2T
Over 38 to 50 [1-1/2 to 2]	35	2T
Over 50 to 60 [2 to 2-1/2]	40	2T
Over 60 to 80 [2-1/2 to 3]	45	2T
Over 80 to 100 [3 to 4]	50	2T
Over 100 to 150 [4 to 6]	60	2T
Over 150 to 200 [6 to 8]	80	2T

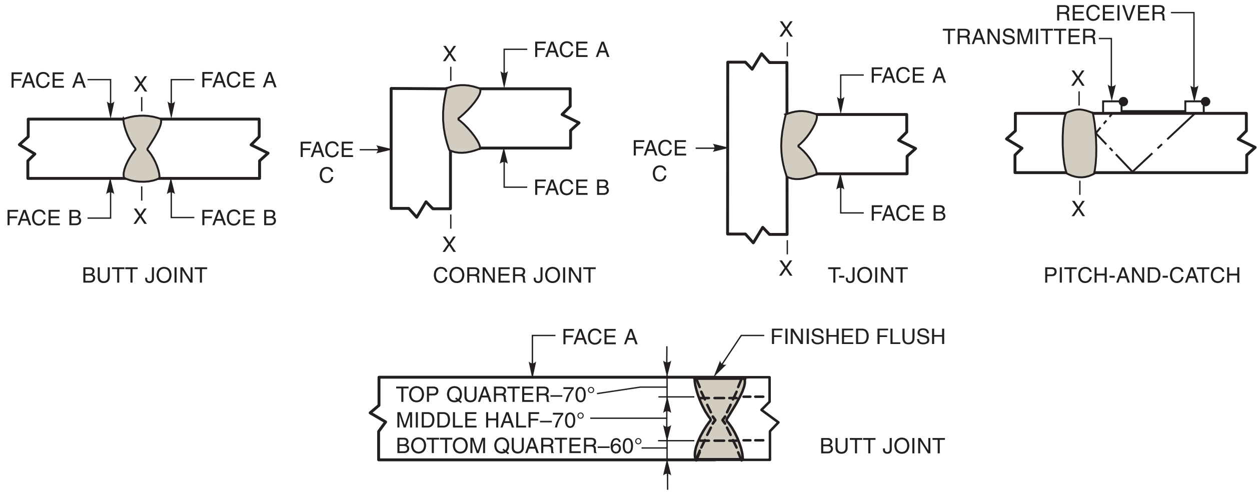
Table 8.2B
Wire IQI Requirements (see 8.10.7)

Nominal Material Thickness Range, mm [in]	Source Side Maximum Wire Diameter, mm [in]
Up to 6 [1/4] incl.	0.25 [0.010]
Over 6 to 10 [1/4 to 3/8]	0.33 [0.013]
Over 10 to 16 [3/8 to 5/8]	0.41 [0.016]
Over 16 to 20 [5/8 to 3/4]	0.51 [0.020]
Over 20 to 38 [3/4 to 1-1/2]	0.63 [0.025]
Over 38 to 50 [1-1/2 to 2]	0.81 [0.032]
Over 50 to 60 [2 to 2-1/2]	1.02 [0.040]
Over 60 to 100 [2-1/2 to 4]	1.27 [0.050]
Over 100 to 150 [4 to 6]	1.60 [0.063]
Over 150 to 200 [6 to 8]	2.54 [0.100]

Table 8.3
Testing Angle (see 8.19.6)

Procedure Chart

Application	Material Thickness, mm [in] 8 [5/16] to 38 [1-1/2]		>38 [1-1/2] to 45 [1-3/4]		>45 [1-3/4] to 60 [2-1/2]		>60 [2-1/2] to 90 [3-1/2]		>90 [3-1/2] to 110 [4-1/2]		>110 [4-1/2] to 130 [5]		>130 [5] to 160 [6-1/2]		>160 [6-1/2] to 180 [7]		>180 [7] to 200 [8]	
		*		*		*		*		*		*		*		*		*
Butt Joint	1	O	1	F	1G or 4	F	1G or 5	F	6 or 7	F	8 or 10	F	9 or 11	F	12 or 13	F	12	F
T-Joint	1	O	1	F or XF	4	F or XF	5	F or XF	7	F or XF	10	F or XF	11	F or XF	13	F or XF	—	—
Corner Joint	1	O	1	F or XF	1G or 4	F or XF	1G or 5	F or XF	6 or 7	F or XF	8 or 10	F of XF	9 or 11	F or XF	13 or 14	F or XF	—	—
ESW/EGW Welds	1	O	1	O	1G or 4	1**	1G or 3	P1 or P3	6 or 7	P3	11 or 15	P3	11 or 15	P3	11 or 15	P3	11 or 15**	P3



Notes:
1. Where possible, all examinations shall be made from Face A and in Leg 1, unless otherwise specified in this Table.
2. Root areas of single groove weld joints that have backing strips not requiring removal by contract shall be tested in Leg 1, where possible, with Face A being that opposite the backing strip. (Grinding of the weld face or testing from additional weld faces may be necessary to allow complete scanning of the weld root.)
3. Examination in Leg II or III shall be made only to satisfy provisions of this table or when necessary to test weld areas made inaccessible by an unground weld surface, or interference with other portions of the weldment, or to meet the requirements of 8.19.6.2.
4. A maximum of Leg III shall be used only where thickness or geometry prevents scanning of complete weld areas and HAZs in Leg I or Leg II.
5. On tension welds on bridges, the top quarter of thickness shall be tested with the final leg of sound progressing from Face B toward Face A, the bottom quarter of thickness shall be tested with the final leg of sound progressing from Face A toward Face B; i.e., the top quarter of thickness shall be tested either from Face A in Leg II or from Face B in Leg I at the Contractor's option, unless otherwise specified in the contract documents.
6. The weld face indicated shall be finished flush before using procedure 1G, 6, 8, 9, 12, 14, or 15. Face A for both connected members shall be in the same plane.

(See Legend and Notes on next page)

Table 8.3 (Continued) Testing Angle (see 8.19.6)

Legend:

X — Check from Face C.
G — Grind weld face flush.
O — Not required.
* — Required only where display reference height indication of discontinuity shall be noted at the weld metal-base metal interface while searching at scanning level with primary procedures selected from first column.
** — Use 400 mm [15 in] or 500 mm [20 in] screen distance calibration.
P — Pitch and catch shall be conducted for further discontinuity evaluation in only the middle half of the material thickness with only 45° or 70° transducers of equal specification, both facing the weld. (Transducers shall be held in a fixture to control positioning—see sketch.) Amplitude calibration for pitch and catch shall normally be made by calibrating a single search unit. When switching to dual search units for pitch and catch inspection, there should be assurance that this calibration does not change as a result of instrument variables.
F — Weld metal-base metal interface indications shall be further evaluated with either 70°, 60°, or 45° transducer—whichever sound path is nearest to being perpendicular to the suspected fusion surface.
Face A — the face of the material from which the initial scanning is done (on T- and corner joints, follow above sketches).
Face B — opposite Face A (same plate).
Face C — the face opposite the weld on the connecting member or a T- or corner joint.

Procedure Legend

	Area of Weld Thickness		
No.	Top Quarter	Middle Half	Bottom Quarter
1	70°	70°	70°
2	60°	60°	60°
3	45°	45°	45°
4	60°	70°	70°
5	45°	70°	70°
6	70°G Face A	70°	60°
7	60° Face B	70°	60°
8	70°G Face A	60°	60°
9	70°G Face A	60°	45°
10	60° Face B	60°	60°
11	45° Face B	70°**	45°
12	70°G Face A	45°	70°G Face B
13	45° Face B	45°	45°
14	70°G Face A	45°	45°
15	70°G Face A	70°A Face B	70°G Face B

Table 8.4
UT Acceptance-Rejection Criteria—Tensile Stress (see 8.26.3.1)

Discontinuity Severity Class	Weld Thickness[a] (mm [in]) and Search Unit Angle										
	8 [5/16] through 20 [3/4]	>20 [3/4] through 38 [1-1/2]	>38 [1-1/2] through 60 [2-1/2]			>60 [2-1/2] through 100 [4]			>100 [4] through 200 [8]		
	70°	70°	70°	60°	45°	70°	60°	45°	70°	60°	45°
Class A	+10 and lower	+8 and lower	+4 and lower	+7 and lower	+9 and lower	+1 and lower	+4 and lower	+6 and lower	–2 and lower	+1 and lower	+3 and lower
Class B	+11	+9	+5 +6	+8 +9	+10 +11	+2 +3	+5 +6	+7 +8	–1 0	+2 +3	+4 +5
Class C	+12	+10	+7 +8	+10 +11	+12 +13	+4 +5	+7 +8	+9 +10	+1 +2	+4 +5	+6 +7
Class D	+13 and up	+11 and up	+9 and up	+12 and up	+14 and up	+6 and up	+9 and up	+11 and up	+3 and up	+6 and up	+8 and up

[a] Weld thickness shall be defined as the nominal thickness of the thinner of the two parts being joined, given in mm [in].

Notes:
1. Class B and C discontinuities shall be separated by at least 2L, L being the length of the longer discontinuity, except that when two or more such discontinuities are not separated by at least 2L, but the combined length of discontinuities and their separation distance shall be equal to or less than the maximum allowable length under the provisions of Class B or C, the discontinuity shall be considered a single acceptable discontinuity.
2. Class B and C discontinuities shall not begin at a distance less than 2L from the end of the weld, L being the discontinuity length.
3. Discontinuities detected at "scanning level" in the root face area of CJP double groove weld joints shall be evaluated using an indicating rating 4 dB more sensitive than described in 8.19.6.5 when such welds are designated as "tension welds" on the drawing (subtract 4 dB from the indication rating "d"). This shall not apply if the weld joint is backgouged to sound metal to remove the root face and MT is used to verify that the root face has been removed.
4. For indications that remain on the display as the search unit is moved, see 8.26.3.2.
5. ESW welds: Discontinuities detected at "scanning level" that exceed 50 mm [2 in] in length shall be suspected as being piping porosity and shall be further evaluated with RT.

Class A (large discontinuities)
Any discontinuity in this category shall be rejected (regardless oflength).

Class B (medium discontinuities)
Any discontinuity in this category having a length greater than 20 mm [3/4 in] shall be rejected.

Class C (small discontinuities)
Any discontinuity in this category having a length greater than 50 mm [2 in] in the middle half or 20 mm [3/4 in] length in the top or bottom quarter of the weld thickness shall be rejected.

Class D (minor discontinuities)
Any discontinuity in this category shall be accepted regardless of length or location in the weld.

Scanning Levels	
Sound Path, mm [in][b]	Above Zero Reference, dB
through 60 [2-1/2]	20
>60 [2-1/2] through 125 [5]	25
>125 [5] through 250 [10]	35
>250 [10] through 400 [15]	45

[b] This column refers to sound path distance; not material thickness.

Table 8.5
UT Acceptance-Rejection Criteria—Compressive Stress (see 8.26.3.1)

Discontinuity Severity Class	Weld Thickness[a] (mm [in]) and Search Unit Angle										
	8 [5/16] through 20 [3/4]	>20 [3/4] through 38 [1-1/2]	>38 [1-1/2] through 60 [2-1/2]			>60 [2-1/2] through 100 [4]			>100 [4] through 200 [8]		
	70°	70°	70°	60°	45°	70°	60°	45°	70°	60°	45°
Class A	+5 and lower	+2 and lower	–2 and lower	+1 and lower	+3 and lower	–5 and lower	–2 and lower	0 and lower	–7 and lower	–4 and lower	–1 and lower
Class B	+6	+3	–1 0	+2 +3	+4 +5	–4 –3	–1 0	+1 +2	–6 –5	–3 –2	0 +1
Class C	+7	+4	+1 +2	+4 +5	+6 +7	–2 to +2	+1 +2	+3 +4	–4 to +2	–1 to +2	+2 +3
Class D	+8 and up	+5 and up	+3 and up	+6 and up	+8 and up	+3 and up	+3 and up	+5 and up	+3 and up	+3 and up	+4 and up

[a] Weld thickness shall be defined as the nominal thickness of the thinner of the two parts being joined, given in mm [in].

Notes:
1. Class B and C discontinuities shall be separated by at least 2L, L being the length of the longer discontinuity, except that when two or more such discontinuities are not separated by at least 2L, but the combined length of discontinuities and their separation distance shall be equal to or less than the maximum allowable length under the provisions of Class B or C, the discontinuity shall be considered a single acceptable discontinuity.
2. Class B and C discontinuities shall not begin at a distance less than 2L from weld ends carrying primary tensile stress, L being the discontinuity length.
3. ESW or EGW welds: Discontinuities detected at "scanning level" that exceed 50 mm [2 in] in length shall be suspected as being piping porosity and shall be further evaluated with RT.
4. For indications that remain on the display as the search unit is moved, see 8.26.3.2.

Class A (large discontinuities)
Any discontinuity in this category shall be rejected (regardless of length).

Class B (medium discontinuities)
Any discontinuity in this category having a length greater than 20 mm [3/4 in] shall be rejected.

Class C (small discontinuities)
Any discontinuity in this category having a length greater than 50 mm [2 in] shall be rejected.

Class D (minor discontinuities)
Any discontinuity in this category shall be accepted regardless of length or location in the weld.

Scanning Levels

Sound Path, mm [in][b]	Above Zero Reference, dB
through 60 [2-1/2]	14
>60 [2-1/2] through 125 [5]	19
>125 [5] through 250 [10]	29
>250 [10] through 400 [15]	39

[b] This column refers to sound path distance; not material thickness.

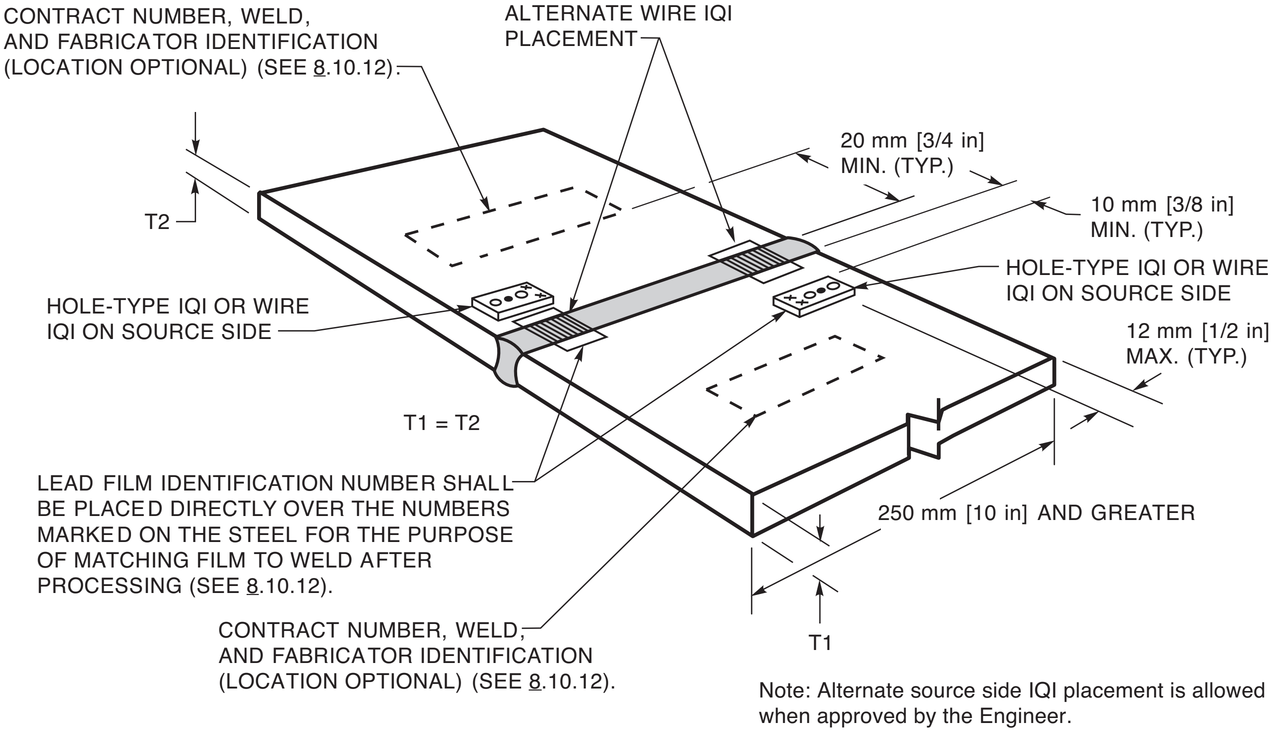


Figure 8.1A—Radiographic Identification and Hole-Type or Wire IQI Locations on Approximately Equal Thickness Joints 250 mm [10 in] and Greater in Length (see 8.10.7)

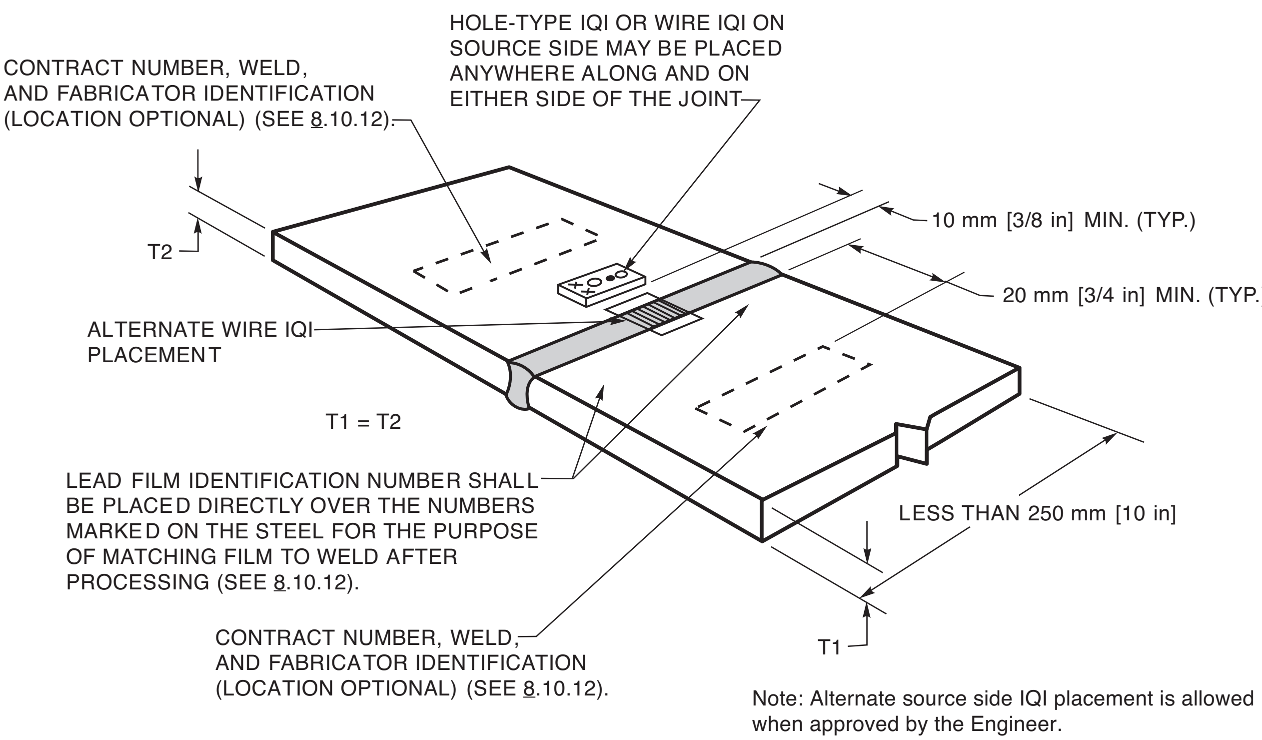


Figure 8.1B—Radiographic Identification and Hole-Type or Wire IQI Locations on Approximately Equal Thickness Joints Less Than 250 mm [10 in] in Length (see 8.10.7)

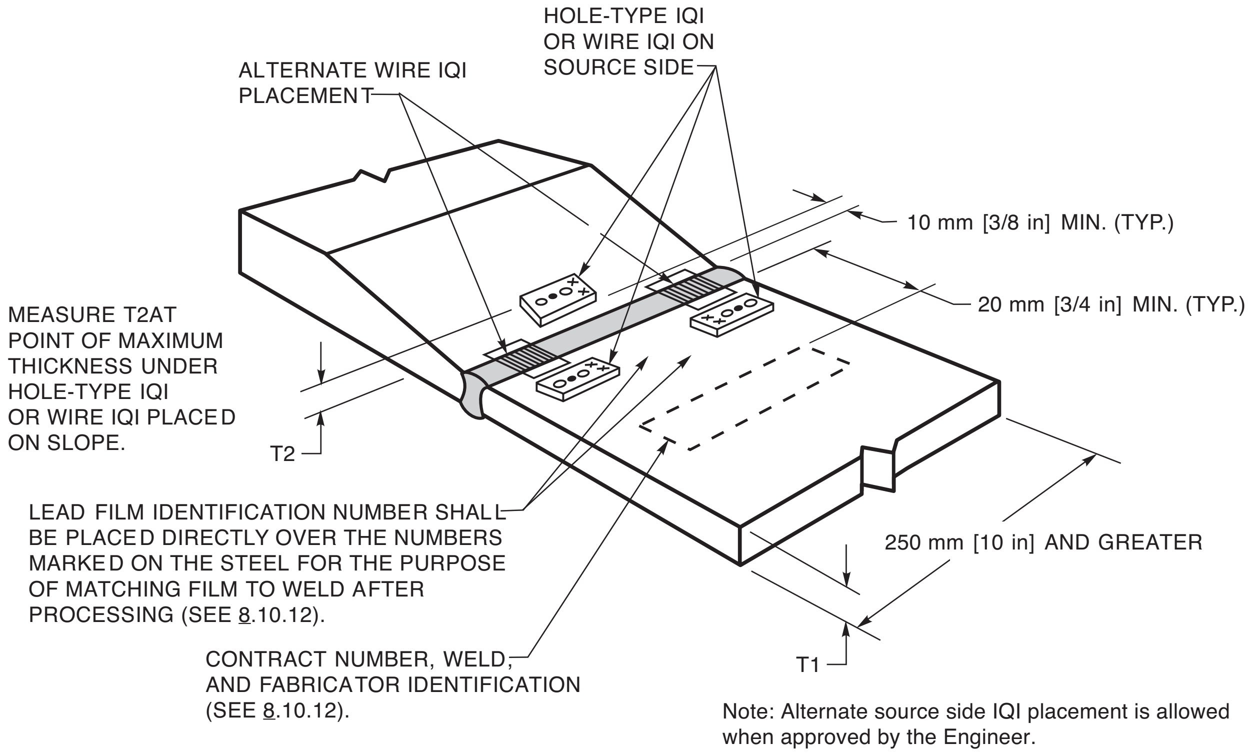


Figure 8.1C—Radiographic Identification and Hole-Type or Wire IQI Locations on Transition Joints 250 mm [10 in] and Greater in Length (see 8.10.7)

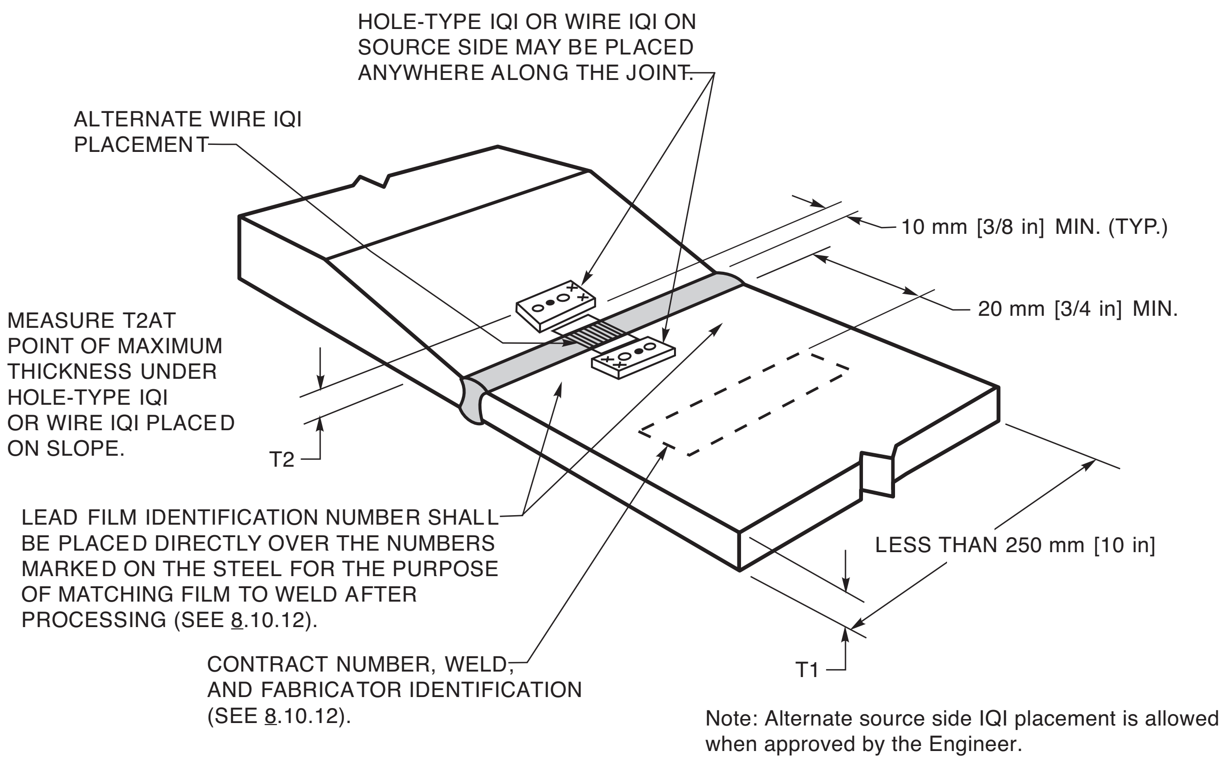


Figure 8.1D—Radiographic Identification and Hole-Type or Wire IQI Locations on Transition Joints Less Than 250 mm [10 in] in Length (see 8.10.7)

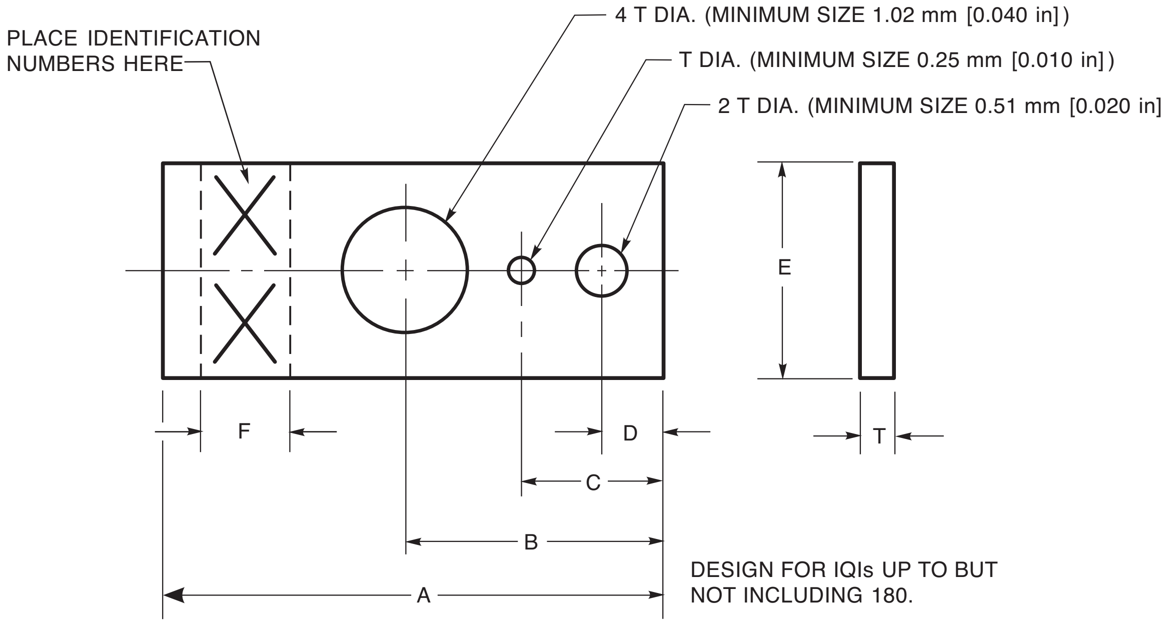


Table of Dimensions of IQI (in mm)

Number (Note a)	A	B	C	D	E	F	IQI Thickness and Hole Diameter Tolerance
5–20	38.10 ± 0.38	19.05 ± 0.38	11.13 ± 0.38	6.35 ± 0.38	12.70 ± 0.38	6.35 ± 0.80	±0.013
4–59	38.10 ± 0.38	19.05 ± 0.38	11.13 ± 0.38	6.35 ± 0.38	12.70 ± 0.38	6.35 ± 0.80	±0.06
0–179	57.15 ± 0.80	34.92 ± 0.80	19.05 ± 0.80	9.52 ± 0.80	25.40 ± 0.80	9.52 ± 0.80	±0.13

Table of Dimensions of IQI (in in)

Number (Note a)	A	B	C	D	E	F	IQI Thickness and Hole Diameter Tolerance
5–20	1.500 ± 0.015	0.750 ± 0.015	0.438 ± 0.015	0.250 ± 0.015	0.500 ± 0.015	0.250 ± 0.030	±0.0005
21–59	1.500 ± 0.015	0.750 ± 0.015	0.438 ± 0.015	0.250 ± 0.015	0.500 ± 0.015	0.250 ± 0.030	±0.0025
60–179	2.250 ± 0.030	1.375 ± 0.030	0.750 ± 0.030	0.375 ± 0.030	1.000 ± 0.030	0.375 ± 0.030	±0.005

[a] IQIs No. 5 through 9 are not 1T, 2T, and 4T.
Note: Holes shall be true and normal to the IQI. Do not chamfer.

Figure 8.1E—Hole-Type IQI Design (see 8.10.7.4)

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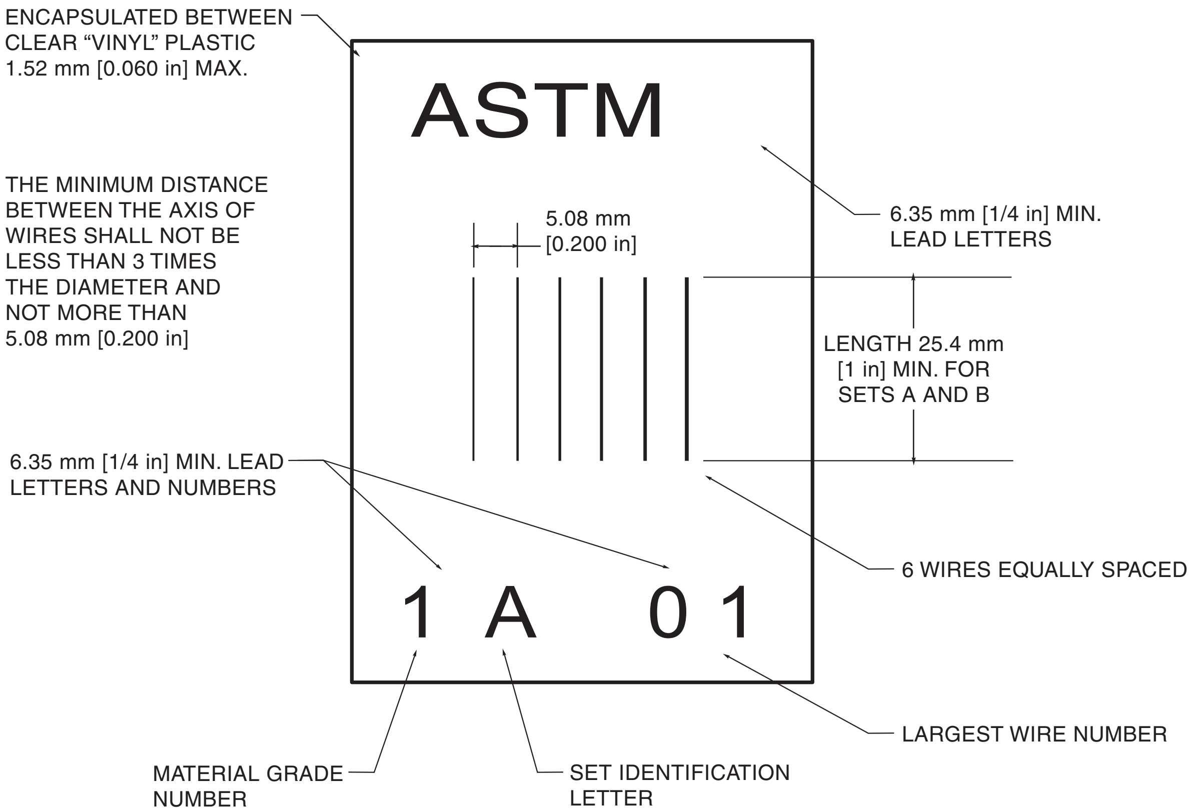

Image Quality Indicator (Wire Penetrameter) Sizes

Wire Diameter, mm [in]			
Set A	Set B	Set C	Set D
0.08 [0.0032]	0.25 [0.010]	0.81 [0.032]	2.5 [0.10]
0.1 [0.004]	0.33 [0.013]	1.02 [0.040]	3.2 [0.126]
0.13 [0.005]	0.4 [0.016]	1.27 [0.050]	4.06 [0.160]
0.16 [0.0063]	0.51 [0.020]	1.6 [0.063]	5.1 [0.20]
0.2 [0.008]	0.64 [0.025]	2.03 [0.080]	6.4 [0.25]
0.25 [0.010]	0.81 [0.032]	2.5 [0.100]	8 [0.32]

Figure 8.1F—Wire-Type IQI (see 8.10.7.5)
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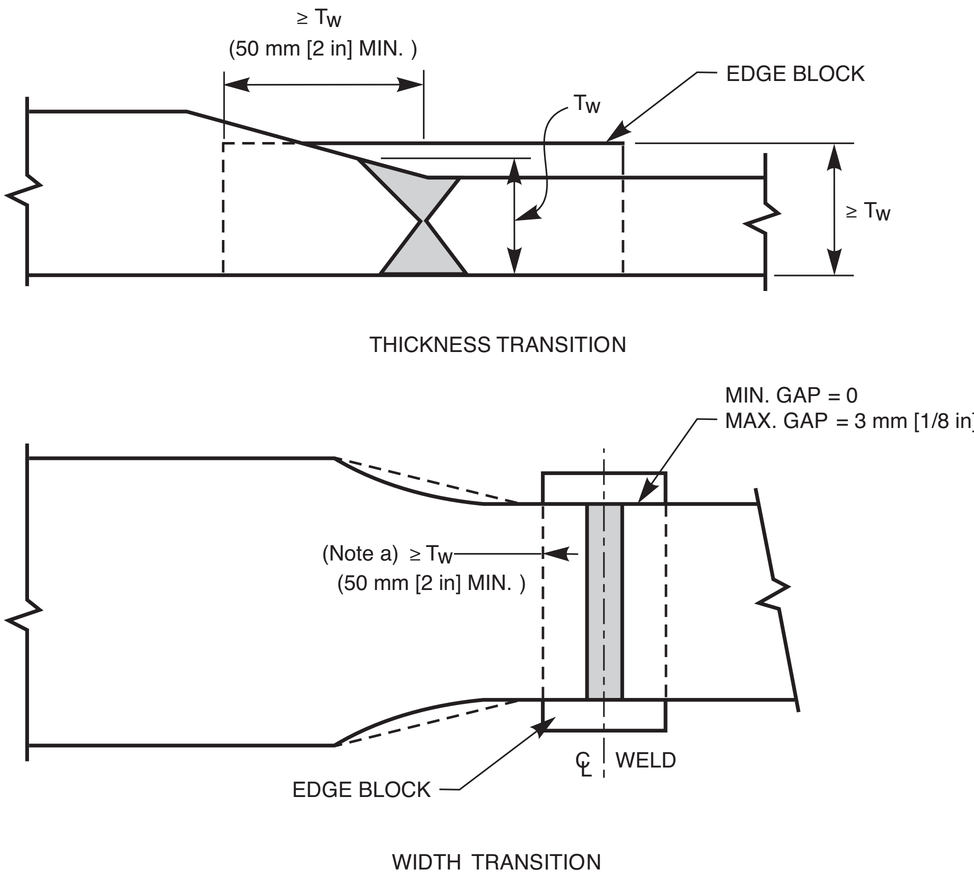


[a] Transition may start beyond edge block.

Note: Edge block shall not be tack welded (see 8.10.14).

Figure 8.2—RT Edge Block Placement

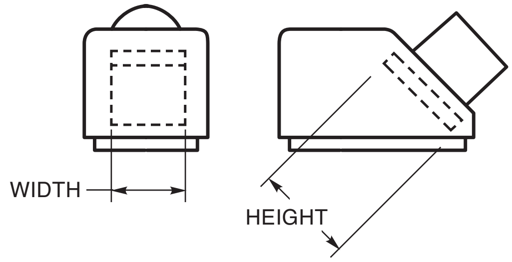


Figure 8.3—Transducer Crystal (see 8.15.7.2)

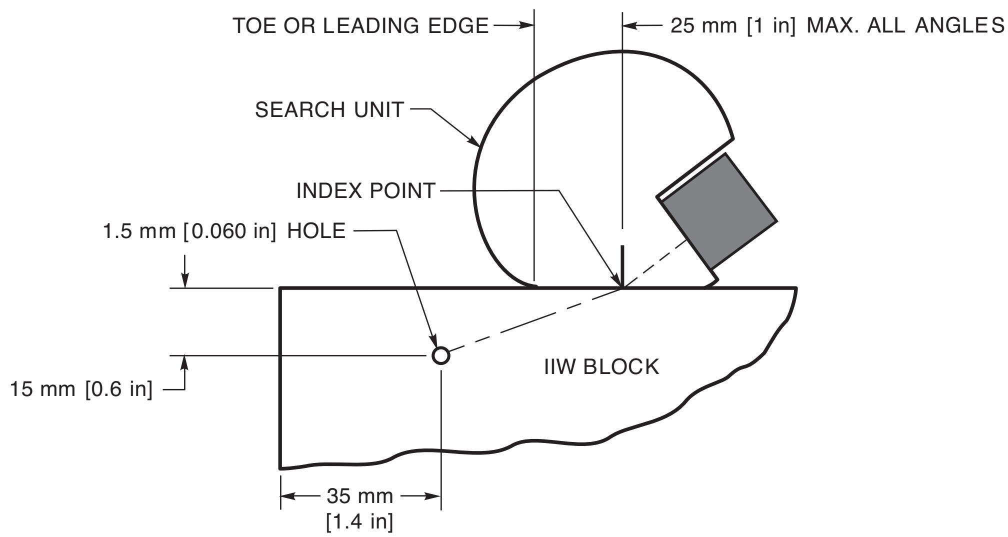
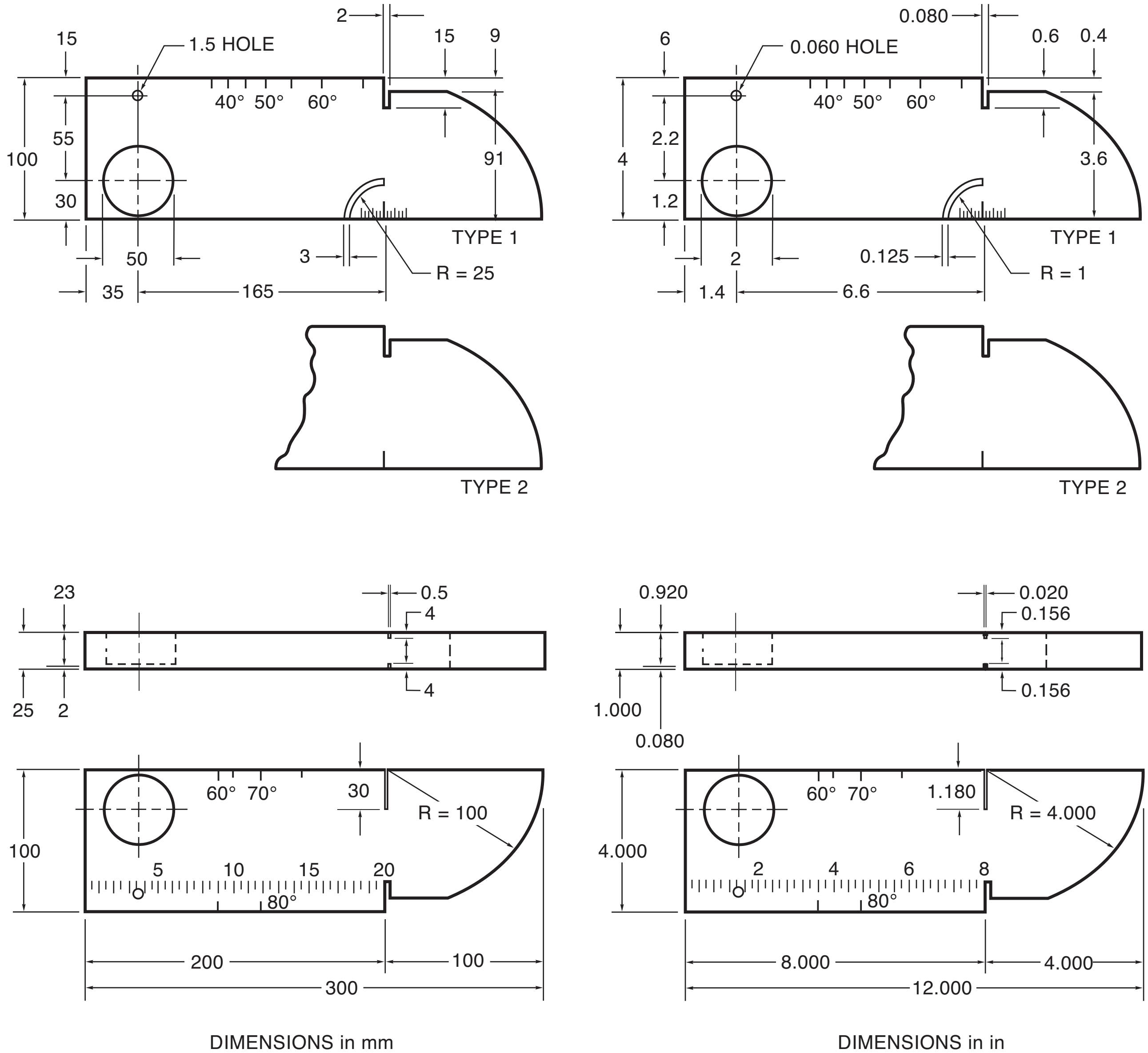


Figure 8.4—Qualification Procedure of Search Unit Using IIW Reference Block (see 8.15.7.6)



Notes:
1. The dimensional tolerance between all surfaces involved in referencing or calibrating shall be within ±0.13 mm [±0.005 in] of detailed dimension.
2. The surface finish of all surfaces to which sound shall be applied or reflected from shall have a maximum of 3 μm [125 μin].
3. All material shall be M 270M (A709) Gr. 250 [36] or acoustically equivalent.
4. All holes shall have a smooth internal finish and shall be drilled at 90° to the material surface.
5. Degree lines and identification markings shall be indented into the material surface so that permanent orientation can be maintained.
6. Other approved reference blocks with slightly different dimensions or distance calibration slot features are allowed.
7. These notes shall apply to all sketches in Figures 8.5A and 8.5B.

Figure 8.5A—International Institute of Welding (IIW) UT Reference Blocks (see 8.16.1)

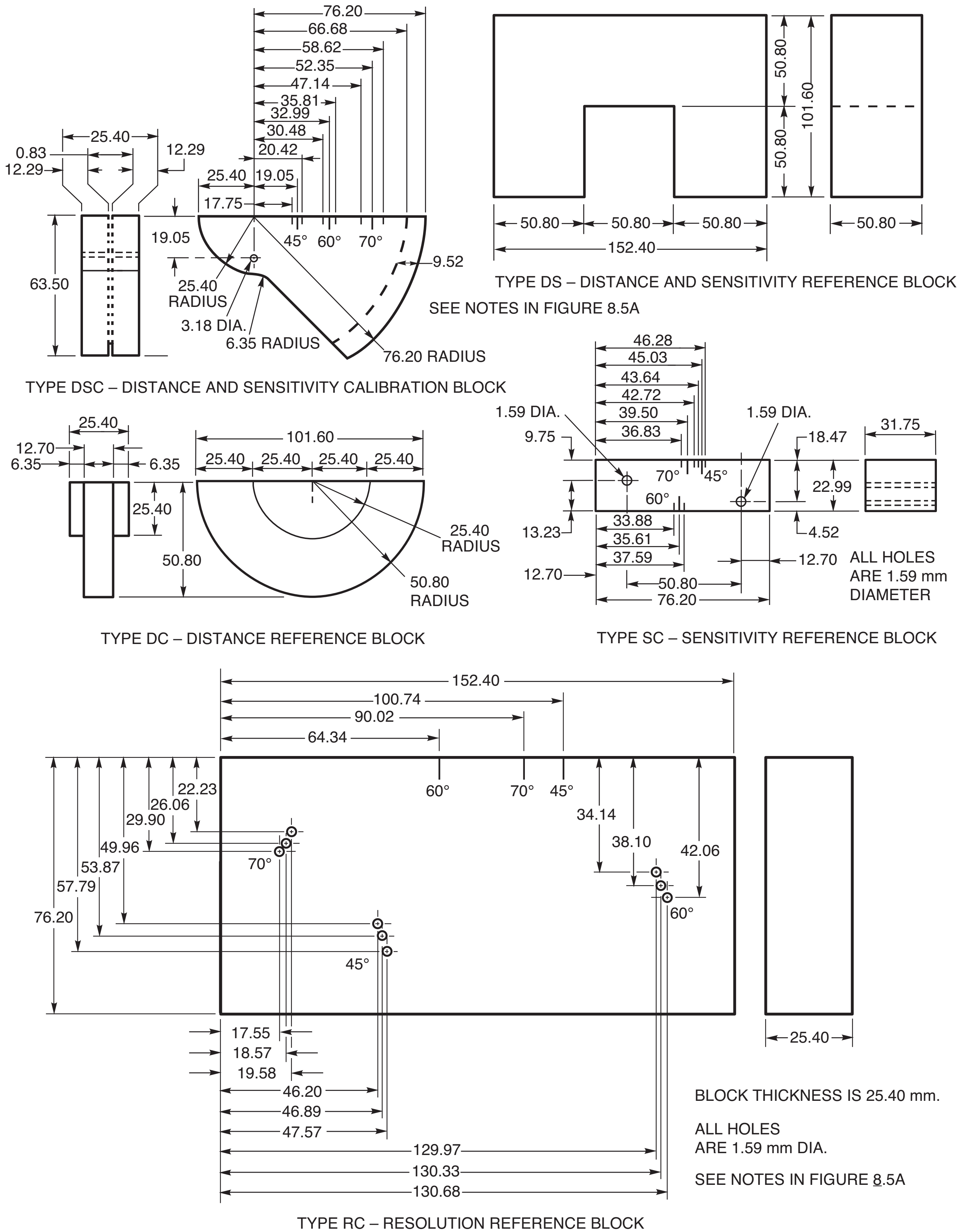


Figure 8.5B—Other Approved UT Reference Blocks (see 8.16.1) [Dimensions in Millimeters]

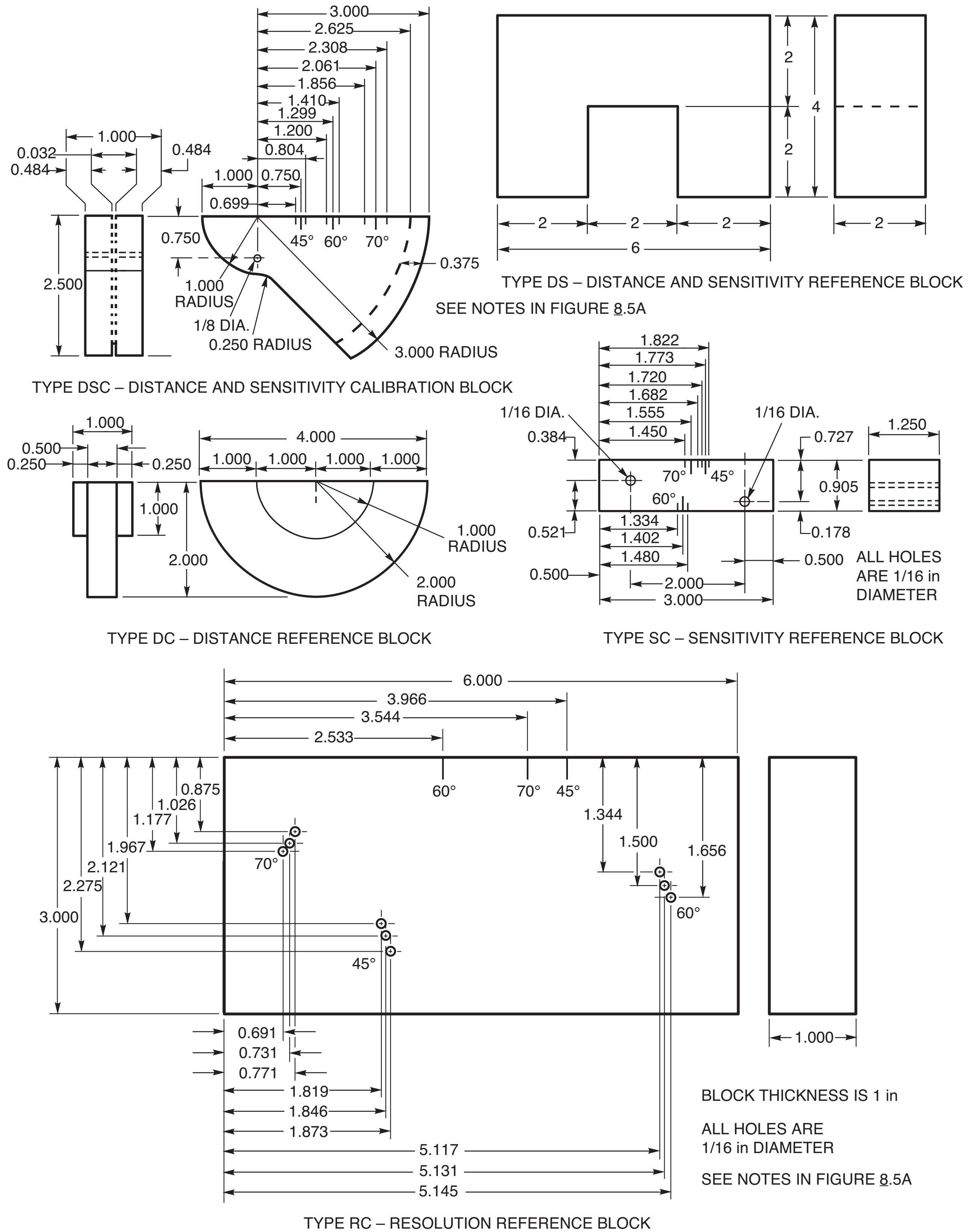


Figure 8.5B (Continued)—Other Approved UT Reference Blocks (see 8.16.1) [Dimensions in Inches]

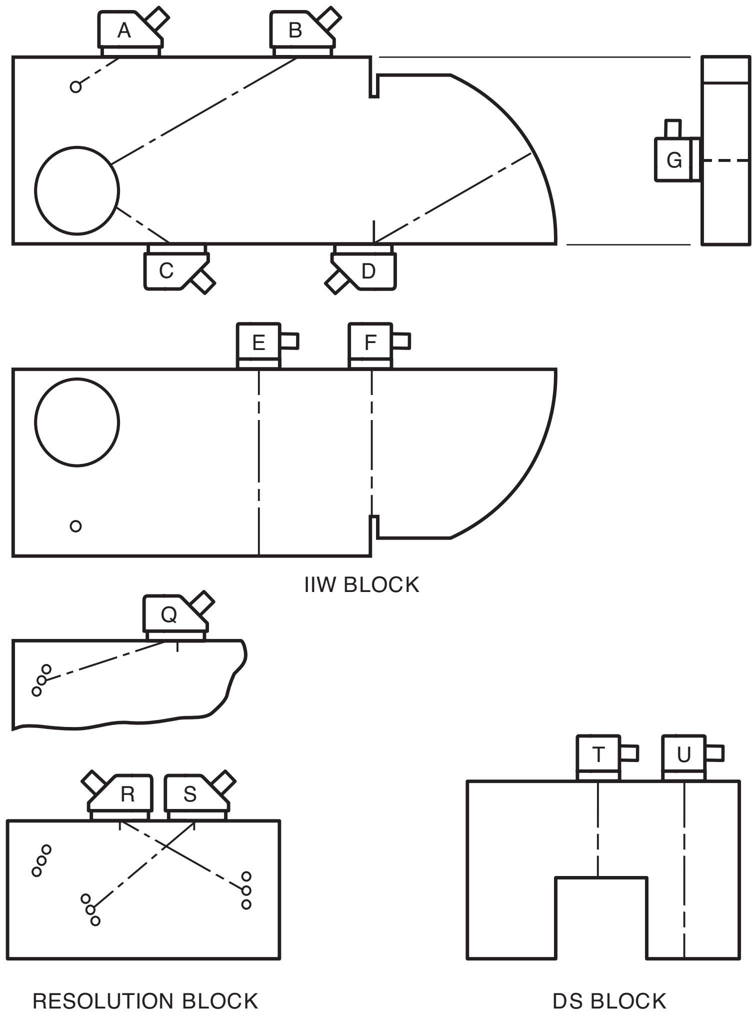
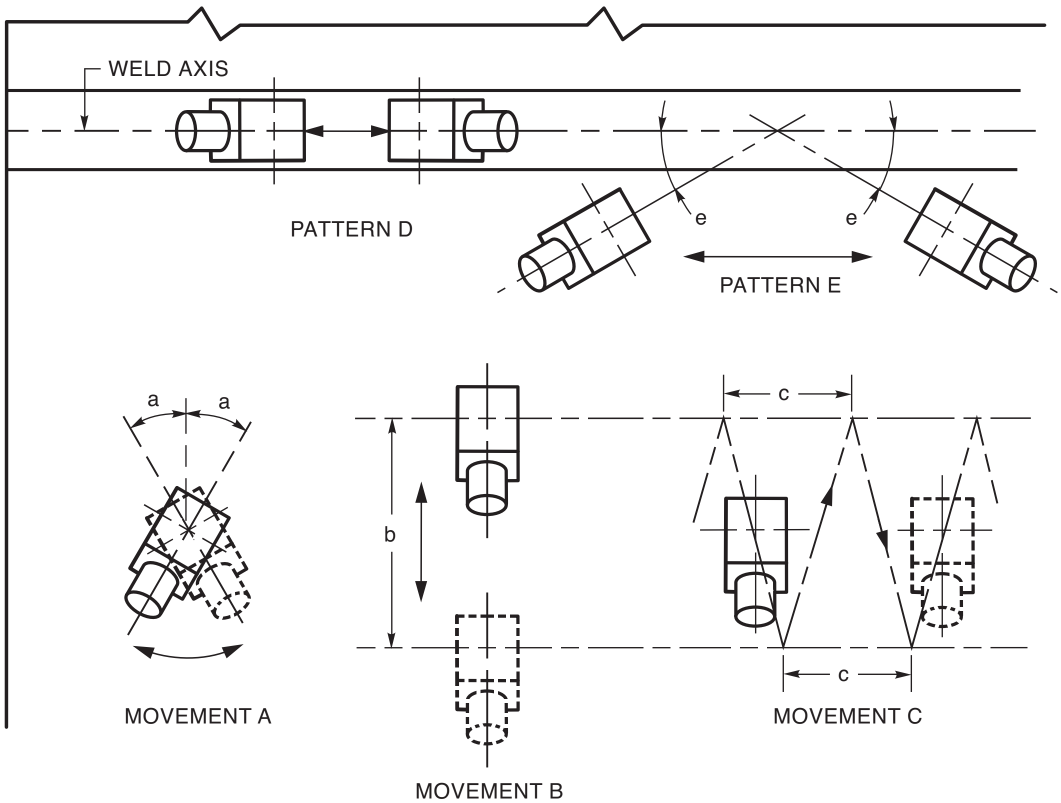
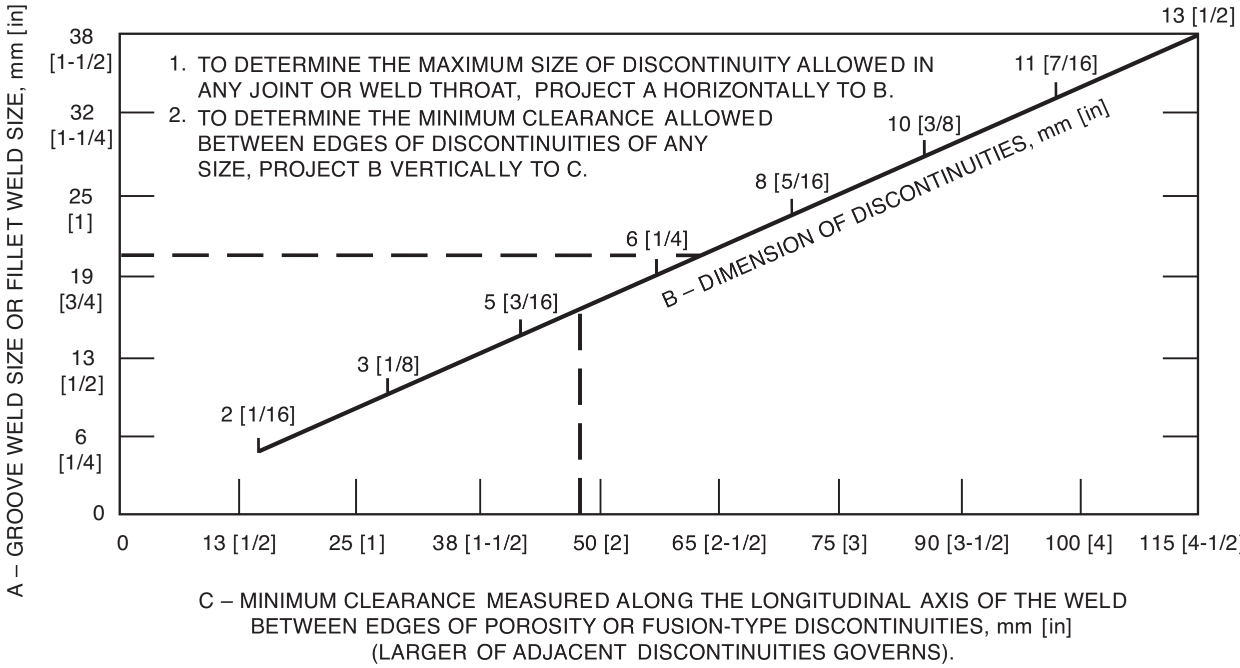


Figure 8.6—Transducer Positions (Typical) (see 8.21)



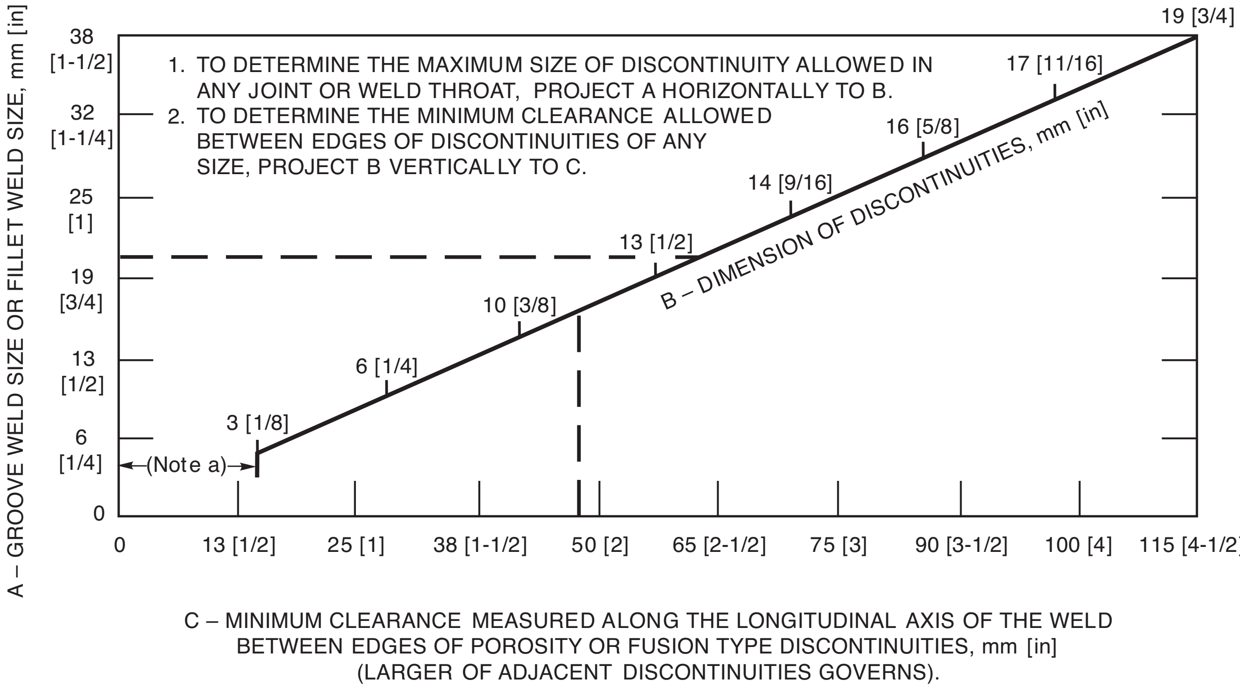
Notes:
1. Testing patterns are all symmetrical around the weld axis with the exception of pattern D, which shall be conducted directly over the weld axis.
2. Testing from both sides of the weld axis shall be to be made wherever mechanically possible.

Figure 8.7—Plan View of UT Scanning Patterns (see 8.24)



Note: Adjacent discontinuities, spaced less than the minimum spacing required, shall be measured as one length equal to the sum of the total length of the discontinuities plus the length of the space between them and evaluated as a single discontinuity.

Figure 8.8—Weld Quality Requirements for Discontinuities Occurring in Tension Welds (Limitations of Porosity and Fusion Discontinuities) (see 8.26.2.1)



[a] The maximum size of a discontinuity located within this distance from an edge of plate shall be 3 mm [1/8 in], but a 3 mm [1/8 in] discontinuity must be 6 mm [1/4 in] or more away from the edge. The sum of discontinuities less than 3 mm [1/8 in] in size and located within this distance from the edge shall not exceed 5 mm [3/16 in]. Discontinuities 2 mm [1/16 in] to less than 3 mm [1/8 in] shall not be restricted in other locations unless they are separated by less than 2 L (L being the length of the larger discontinuity); in which case, the discontinuities shall be measured as one length equal to the total length of the discontinuities and space and evaluated as shown in Figure 8.9.

Figure 8.9—Weld Requirements for Discontinuities Occurring in Compression Welds (Limitations of Porosity or Fusion Type Discontinuities) (see 8.26.2.2)

9. Stud Welding

9.1 Scope

Clause 9 contains general requirements for welding steel studs to steel (see 9.2.7 and 1.2.2 for approved steels). In addition, it stipulates specific requirements for the following:

(1) Workmanship, preproduction testing, operator qualification, and application qualification testing, when required, all to be performed by the Contractor

(2) QC and QA inspection of stud welding during production

(3) Mechanical properties of steel studs, and requirements for qualification of stud bases, all tests and documentation to be furnished by the stud manufacturer

9.2 General Requirements

9.2.1 Studs shall be of suitable design for arc welding to steel members with the use of automatically timed stud welding equipment. The type and size of the stud shall be as specified by the drawings, specifications, or special provisions. For headed-type studs, see Figure 9.1.

9.2.2 An arc shield (ferrule) of heat-resistant ceramic or other suitable material shall be furnished with each stud.

9.2.3 A suitable deoxidizing and arc stabilizing flux for welding shall be furnished with each stud of 8 mm [5/16 in] diameter or larger. Studs less than 8 mm [5/16 in] in diameter may be furnished with or without flux.

9.2.4 Only studs with qualified stud bases shall be used. A stud base, to be qualified, shall have passed the test described in Annex D. The arc shield used in production shall be the same as used in qualification tests or as recommended by the manufacturer. Qualification of stud bases in conformance with Annex D shall be at the manufacturer's expense.

9.2.5 Finish shall be produced by heading, rolling, or machining. Finished studs shall be of uniform quality and condition, free of injurious laps, fins, seams, cracks, twists, bends, or other injurious discontinuities. Radial cracks or bursts in the head of a stud shall not be cause for rejection, provided that the cracks or bursts do not extend more than half the distance from the head periphery to the shank, as determined by visual inspection.

9.2.6 Only bases qualified under Annex D shall be used. When requested by the Engineer, the Contractor shall provide the following information:

(1) A description of the stud and arc shield

(2) Certification from the manufacturer that the stud base is qualified as described in 9.2.4

(3) Qualification test data

9.2.7 AASHTO M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W] steel shall not be stud welded without approval of the Engineer.

9.3 Mechanical Requirements

9.3.1 Studs shall be made from cold-drawn bar stock conforming to the requirements of ASTM A108, *Standard Specification for Steel Bar, Carbon, and Alloy, Cold-Finished,* Grades G10100 through G10200, inclusive, either semi-killed or killed deoxidation.

9.3.1.1 Mechanical property requirements of studs other than outlined below shall be specified by the Engineer.

9.3.1.2 At the manufacturer's option, mechanical properties of studs shall be determined by testing either (1) the steel after cold finishing, or (2) the full diameter finished studs. In either case, the studs shall conform to the requirements shown in Table 9.1.

9.3.2 Mechanical properties shall be determined in conformance with the applicable sections of ASTM A370, *Test Methods and Definitions for Mechanical Testing of Steel Products*. A typical test fixture is used, similar to that shown in Figure 9.2.

9.3.3 Upon request by the Engineer, the Contractor shall furnish the following:

9.3.3.1 The Contractor shall provide the stud manufacturer's certification that the studs, as delivered, conform to the applicable requirements of 9.2 and 9.3.

9.3.3.2 The Contractor shall provide certified copies of the stud manufacturer's test reports covering the last completed set of in-plant quality control mechanical tests, required by 9.3 for each stock size delivered. The quality control test shall have been made within the six month period before delivery of the studs.

9.3.4 When quality control tests are not available, the Contractor shall furnish mechanical test reports conforming to the requirements of 9.3. The mechanical tests shall be on finished studs provided by the manufacturer of the studs. The number of tests to be performed shall be specified by the Engineer.

9.3.5 The Engineer may select studs of each type and size used under the contract as necessary for checking the requirements of 9.2 and 9.3. Furnishing these studs shall be at the Contractor's expense. Testing shall be at the Owner's expense.

9.4 Workmanship

9.4.1 At the time of welding, the studs shall be free from rust, rust pits, scale, oil, moisture, and other deleterious matter that would adversely affect the welding operation.

9.4.2 The stud base shall not be painted, galvanized, nor cadmium-plated prior to welding.

9.4.3 The areas to which the studs are to be welded shall be free of scale, rust, moisture, and other injurious material to the extent necessary to obtain satisfactory welds. These areas may be cleaned by wire brushing, scaling, prick-punching, or grinding. Extreme care should be exercised when welding through metal decking.

9.4.4 The arc shields or ferrules shall be kept dry. Any arc shields showing signs of surface moisture from dew or rain shall be oven dried at 120°C [250°F] for two hours before use.

9.4.5 Longitudinal and lateral spacings of stud shear connectors (Type B) with respect to each other and to edges of beam or girder flanges may vary a maximum of 25 mm [1 in] from the location shown in the drawings. The clear distance between studs shall not be less than 25 mm [1 in] unless approved by the Engineer. The minimum distance from the edge of a stud base to the edge of a flange shall be the diameter of the stud plus 3 mm [1/8 in] but preferably not less than 40 mm [1-1/2 in].

9.4.6 After welding, arc shields shall be broken free from studs to be embedded in concrete and, where practical, from all other studs.

9.4.7 The studs, after welding, shall be free of any discontinuities or substances that would interfere with their intended function. However, nonfusion on the legs of the flash and small shrink fissures are acceptable. The fillet weld profiles shown in Figure 5.4 do not apply to the flash of automatically timed stud welds. The expelled metal around the base of the stud shall be designated as flash in conformance with Clause 3 of this code. It shall not be defined as a fillet weld such as those formed by conventional arc welding. The stud weld flash may have nonfusion in its vertical leg and overlap on its horizontal leg, and it may contain occasional small shrink fissures or other discontinuities that usually form at the top of the weld flash with essentially radial or longitudinal orientation, or both, to the axis of the stud. Such nonfusion, on the vertical leg of the flash, and small shrink fissures shall be acceptable.

9.5 Technique

9.5.1 Studs shall be welded with automatically timed stud welding equipment connected to a suitable source of direct current electrode negative (DCEN) power. Welding voltage, current, time, and gun settings for lift and plunge should be set at optimum settings, based on past practice, recommendations of stud and equipment manufacturer, or both. The AWS Welding Handbook should also be used for technique guidance.

9.5.2 If two or more stud welding guns are to be operated from the same power source, they shall be interlocked so that only one gun can operate at a time, and so that the power source has fully recovered from making one weld before another weld is started.

9.5.3 While in operation, the welding gun shall be held in position without movement until the weld metal has solidified.

9.5.4 Welding shall not be done when the base metal temperature is below –20°C [0°F] or when the surface is wet or exposed to falling rain or snow.

9.5.4.1 When the temperature of the base metal is below 0°C [32°F], one additional stud in each 100 studs welded shall be tested by methods described in 9.7.1.3 and 9.7.1.4, except that the angle of testing shall be approximately 15°. This is in addition to the first two studs tested for each start of a new production period or change in setup.

9.5.4.2 Setup includes stud gun, power source, stud diameter, gun lift and plunge, total welding lead length, or changes greater than ±5% in current (amperage) and time.

9.5.5 At the option of the Contractor, studs may be fillet welded by SMAW, provided the following requirements shall be met:

9.5.5.1 The minimum fillet size to be used shall be the larger of those required in Table 4.1 or 9.2.

9.5.5.2 Welding shall be done with low-hydrogen electrodes 4.0 mm [5/32 in] or 4.8 mm [3/16 in] in diameter except that a smaller diameter electrode may be used on studs 10 mm [3/8 in] or less in diameter or for out-of-position welds.

9.5.5.3 The stud base shall be prepared so that the base of the stud fits against the base metal.

9.5.5.4 All rust and mill scale at the location of the stud shall be removed from the base metal. The end of the stud shall also be clean.

9.5.5.5 The base metal to which studs are welded shall be preheated in conformance with the requirements of Table 6.3.

9.5.5.6 Fillet welded stud bases shall be visually inspected per 8.5.

9.6 Stud Application Qualification Requirements

9.6.1 Prequalification. Studs that are shop or field applied in the flat (down-hand) position to a planar and horizontal surface shall be deemed prequalified by virtue of the manufacturer's stud-base qualification tests Annex D, and no further application testing is required. The limit of flat position is defined as 0° to 15° slope on the surface to which the stud is applied.

The following are some nonprequalified stud applications that require tests of this section:

(1) Studs that are applied on nonplanar surfaces or to a planar surface in the vertical or overhead positions.

(2) Studs that are welded through decking. The tests should be with material representative of the condition to be used in construction.

(3) Studs welded to steels other than those described in 1.2.2.

9.6.2 Responsibilities for Tests. The Contractor or stud applicator shall be responsible for the performance of these tests. Tests may be performed by the Contractor or stud applicator, the stud manufacturer, or by another testing agency satisfactory to all parties involved.

9.6.3 Preparation of Specimens

9.6.3.1 Test specimens shall be prepared by welding the studs being qualified to specimen plates of AASHTO M 270M/M 270(A709/A709M) Grade 250 [36] steel or any base metal described in 1.2.2.

9.6.3.2 Weld position, nature of base metal and stud surfaces, current, and time shall be recorded.

9.6.4 Number of Specimens. 10 specimens shall be welded consecutively using recommended WPSs and settings for each diameter, position, and surface geometry.

9.6.5 Tests Required. The 10 specimens shall be tested using one or more of the following test methods: bending, torquing, or tensioning.

9.6.6 Test Methods

9.6.6.1 Bend Test. Studs shall be bend tested by being bent 90° from their original axis. A stud application shall be considered qualified if all the test specimens are bent 90° and fracture occurs in the plate or shape material or in the shank of the stud and not in the weld.

9.6.6.2 Torque Test. Studs shall be torque tested using a torque-test arrangement that is substantially in conformance with Figure 9.3. A stud application shall be considered qualified if all test specimens are torqued to destruction without failure in the weld.

9.6.6.3 Tension Test. Studs shall be tension tested to destruction using any machine capable of supplying the required force. A stud application shall be considered qualified if none of the test specimens fail in the weld.

9.6.7 Application Qualification Test Data shall include the following:

(1) Drawings that show shapes and dimensions of studs and arc shields

(2) A complete description of stud and base materials and a description (part number) of the arc shield

(3) Welding position and settings (current, time)

(4) A record which shall be made for each qualification and that record shall be available for each contract

9.7 Production Control

9.7.1 Preproduction Testing

9.7.1.1 Before production welding with a particular setup (see 9.5.4.2) and with a given size and type of stud, and at the beginning of each day's or shift's production, testing shall be performed on the first two studs that are welded. The stud technique may be developed on a piece of material similar to the production member in thickness and properties. If actual production thickness is not available, the thickness may vary by plus or minus 25%. All test studs shall be welded in the same general position as required on the production member (flat, vertical, or overhead).

9.7.1.2 Instead of being welded to separate material, the test studs may be welded on the production member, except when separate plates are required by 9.7.1.5.

9.7.1.3 The test studs shall be visually examined. They shall exhibit full 360° flash.

9.7.1.4 In addition to visual examination, the test shall consist of bending the studs after they are allowed to cool, to an angle of approximately 30° from their original axes by either striking the studs on the head with a hammer or placing a pipe or other suitable hollow device over the stud and manually or mechanically bending the stud. At temperatures below 10°C [50°F], bending shall preferably be done by continuous slow application of load. For threaded studs, the torque test of Figure 9.3 shall be substituted for the bend test.

9.7.1.5 If on visual examination the test studs do not exhibit 360° flash, or if on testing, failure occurs in the weld zone of either stud, the WPS shall be corrected, and two more studs shall be welded to separate material or on the production member and tested in conformance with the provisions of 9.7.1.3 and 9.7.1.4. If either of the second two studs fails, additional welding shall be continued on separate plates until two consecutive studs are tested and found to be satisfactory before any more production studs are welded to the member.

9.7.2 Production Welding. Once production welding has begun, any changes made to the welding setup (see 9.5.4.2) as determined in 9.7.1 shall require that the testing in 9.7.1.3 and 9.7.1.4 be performed prior to resuming production welding.

9.7.3 In production, studs on which a full 360° flash is not obtained may, at the option of the Contractor, be repaired by adding the minimum fillet weld as required by 9.5.5 in place of the missing flash. The repair weld shall extend at least 10 mm [3/8 in] beyond each end of the discontinuity being repaired.

9.7.4 Operator Qualification

9.7.4.1 The preproduction test required by 9.7.1, if successful, shall also serve to qualify the stud welding operator.

9.7.4.2 Before any production studs are welded by an operator not involved in the preproduction setup of 9.7.1, the first two studs welded by the operator shall be tested in conformance with 9.7.1.3 and 9.7.1.4. When two consecutively welded studs have been tested and found satisfactory, the operator may then weld production studs.

9.7.5 Base Metal Damage from Failed Studs.

9.7.5.1 Components Subject to Calculated Tensile Stress. If an unacceptable stud has been removed from a component subjected to calculated tensile stresses and no base metal has been pulled out, the area from which the stud was removed shall be finished with no surface irregularities exceeding either 1 mm [1/32 in.] parallel to calculated tensile stress or 0.25 mm (0.010 in.) perpendicular to calculated tensile stress.

Where base metal has been pulled out by stud failure, all resulting fractured and projecting material shall be removed. If the maximum removal depth does not exceed 5 mm [3/16 in.] or 20% of the component thickness, whichever is less, and after finishing, the remaining net cross-sectional section area of the member component (e.g., flange) is at least 98% of its nominal cross-sectional area, no repair weld is needed, and the damaged area shall be faired to the surface at a slope not exceeding 1 in 10.

If damage exceeds any of the preceding limits, the depression shall be filled by welding in conformance with this code, and the weld surface shall be finished flush. A WPS in conformance with this code shall be used to fill the depression, and the weld surface shall be finished flush.

Machine or grinding marks from final finishing shall be parallel to the calculated tensile stress with no irregularities above or below the surface exceeding either 1 mm [1/32 in.] parallel to tensile stress or 0.25 mm [0.010 in.] perpendicular to tensile stress.

9.7.5.2 Components Only Subject to Compressive Stress. In compression areas of members, if stud failures are confined to shanks or fusion zones of studs, a new stud may be welded adjacent to each unacceptable area in lieu of repair and replacement on the existing weld area, if stud spacing permits (see 9.4.5). Surface finishing of the stud removal area is not required in this case.

If base metal is pulled out by stud failure, the repair provisions shall be the same as for areas subject to calculated tension (see 9.7.5.1), except final finishing may be in any direction and deviations from the local surface are limited to a maximum of 1 mm [1/32 in.] in all directions.

9.7.5.3 Stud Replacement. Where a replacement stud is to be installed at the existing location, any necessary base-metal repairs shall be made prior to stud installation. If a replacement stud will be welded in the same location, FCAW-S or SAW with active flux shall not be used for base metal repair welding.

9.7.5.4 Replacement studs (other than threaded type that should be torque tested) shall be tested by bending to an angle of approximately 15° from their original axis.

9.7.5.5 The areas of components exposed to view in completed structures shall be made smooth and flush where a stud has been removed.

9.8 Inspection Requirements

9.8.1 If visual inspection reveals any stud that does not show a full 360° flash or any stud that has been repaired by welding, such stud shall be bent to an angle of approximately 15° from its original axis.

9.8.2 The method of bending shall be in conformance with 9.7.1.4. The direction of bending for studs with less than a 360° flash shall be opposite to the missing portion of the flash.

9.8.3 Threaded studs shall be torque tested. Torque testing shall be in conformance with Figure 9.3.

The Inspector, where conditions warrant, may select a reasonable number of additional studs to be subjected to the tests described in 9.8.1.

9.8.4 The bent stud shear connectors (Type B) and other studs to be embedded in concrete (Type A) that show no sign of failure shall be acceptable for use and left in the bent position. All bending and straightening when required shall be done without heating, before completion of the production stud welding operation, except as otherwise provided in the contract.

9.8.5 If, in the judgment of the Engineer, studs welded during the progress of the work are not in conformance with code provisions, as indicated by inspection and testing, corrective action shall be required of the Contractor at the Contractor's expense. The Contractor shall make the setup changes necessary to ensure that studs subsequently welded will meet code requirements.

9.8.6 At the option and the expense of the Owner, the Contractor may be required, at any time, to submit studs of the types used under the contract for a qualification check in conformance with the procedures of Annex D.

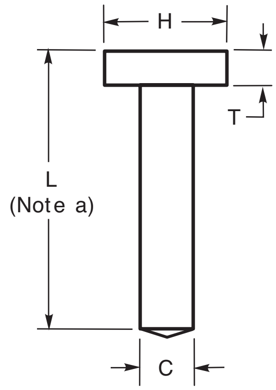
Table 9.1
Mechanical Property Requirements for Studs (see 9.3.1.2)

	Type A[a]	Type B[b]
Tensile Strength	380 MPa [55 ksi] min.	415 MPa [60 ksi] min.
Yield Strength (0.2% offset)	-	345 MPa [50 ksi] min.
Elongation (% in 50 mm [2 in])	17% min.	20% min.
Reduction of area	50% min.	50% min.

[a] Type A studs shall be general purpose of any type and size used for purposes other than shear transfer in composite beam design and construction.
[b] Type B studs shall be studs that are headed, bent, or of other configuration in 12 mm [1/2 in] through 23 mm [7/8 in] diameter that are used as an essential component in composite beam design and construction.

Table 9.2
Minimum Fillet Weld Size for Small Diameter Studs (see 9.5.5.1)

Stud Diameter, ϕ, mm [in]	Minimum Fillet Weld Size, mm [in]
$\phi \leq 10$ [3/8]	6 [1/4]
10 [3/8] $< \phi \leq 25$ [1]	8 [5/16]
$\phi > 25$ [1]	10 [3/8]



[a] L = manufactured length—length specified by Engineer plus upset distance.

Standard Dimenstions, mm [in]					
	Shank Diameter (C)		Length Tolerance (L)	Head Diameter (H)	Minimum Head Height (T)
12.7 [1/2]	+0.00 –0.25 [–0.010]		±1.6 [±1/16]	25.4 ± 0.4 [1 ± 1/64]	7.1 [9/32]
15.9 [5/8]	+0.00 –0.25 [–0.010]		±1.6 [±1/16]	31.7 ± 0.4 [1-1/4 ± 1/64]	7.1 [9/32]
19.0 [3/4]	+0.00 –0.38[–0.015]		±1.6 [±1/16]	31.7 ± 0.4 [1-1/4 ± 1/64]	9.5 [3/8]
22.1 [7/8]	+0.00 –0.38[–0.015]		±1.6 [±1/16]	34.9 ± 0.4 [1-3/8 ± 1/64]	9.5 [3/8]
25.4 [1]	+0.00 –0.38[–0.015]		±1.6 [±1/16]	41.3 ± 0.4 [1-5/8 ± 1/64]	12.7 [1/2]

Figure 9.1—Dimension and Tolerances of Standard-Type Shear Connectors (see 9.2.1)

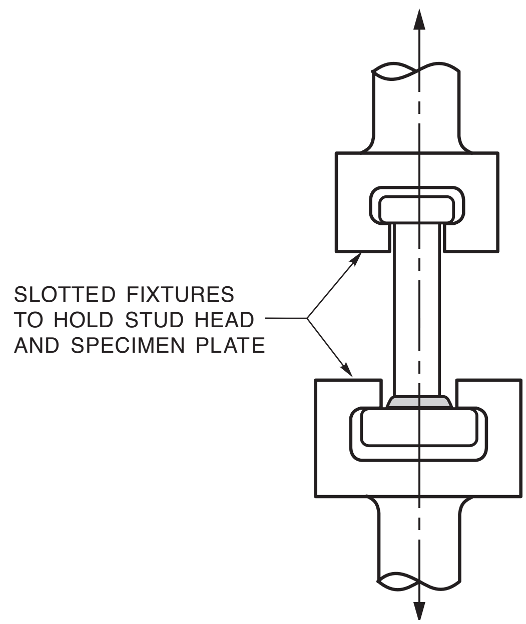
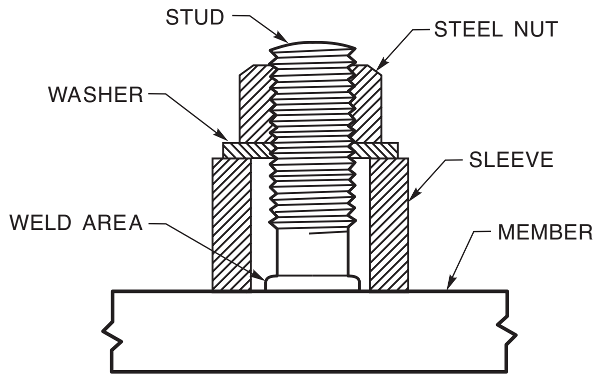


Figure 9.2—Typical Tension Test Fixtures (see 9.3.2)



Note: The dimensions shall be appropriate to the size of the stud. The threads of the stud shall be clean and free of lubricant other than the residue of cutting oil.

Required Torque for Testing Threaded Studs

Nominal Diameter and Thread Pitch (mm)	Testing Torque (J)
M 6 x 1	6
M 8 x 1.25	12
M 10 x 1.5	20
M 12 x 1.75	50
M 14 x 2	73
M 16 x 2	100
M 20 x 2.5	180
M 22 x 2.5	285
M 24 x 3	430

Required Torque for Testing Threaded Studs

Nominal Diameter of Studs [in]	Threads per inch and Series Designated	Testing Torque (ft·lb)
1/4	28 UNF	5.0
1/4	20 UNC	4.2
5/16	24 UNF	9.5
5/16	18 UNC	8.6
3/8	24 UNF	17.0
3/8	16 UNC	15.0
7/16	20 UNF	27.0
7/16	14 UNC	24.0
1/2	20 UNF	42.0
1/2	13 UNC	37.0
9/16	18 UNF	60.0
9/16	12 UNC	54.0
5/8	18 UNF	84.0
5/8	11 UNC	74.0
3/4	16 UNF	147.0
3/4	10 UNC	132.0
7/8	14 UNF	234.0
7/8	9 UNC	212.0
1.0	12 UNF	348.0
1.0	8 UNC	318.0

Figure 9.3—Torque Testing Arrangement and Table of Testing Torques (see 9.6.6.2)

10. Tubular Structures

NO APPLICATIONS WITHIN THIS CODE

11. Strengthening and Repairing Existing Structures

NO APPLICATIONS WITHIN THIS CODE

12. AASHTO/AWS Fracture Control Plan (FCP) for Nonredundant Members

12.1 General Provisions

This clause shall apply to fracture critical nonredundant members. All steel bridge members and member components designated on the plans or elsewhere in the contract documents as fracture critical shall be subject to the additional provisions of this clause. All other provisions of the code shall apply to the construction of fracture critical members (FCMs), except as modified or supplemented herein. Should any provision of this clause be in conflict with other provisions of the code, the requirements of this clause shall apply.

12.2 Definitions

12.2.1 Fracture Control Plan (FCP). The designation "FCP" shall mean fracture control plan and shall include all provisions of Clause 12.

12.2.2 Fracture Critical Member (FCM). AASHTO LRFD Bridge Design Specifications define an FCM as a steel primary member or portion thereof subject to tension whose failure would probably cause a portion of or the entire bridge to collapse.

12.2.2.1 Attachments. Any attachment welded to a tension zone of an FCM, except for bearing sole plates, shall be considered an FCM when any dimension of the attachment exceeds 100 mm [4 in] in the direction parallel to the calculated tensile stress in the FCM. Attachments designated FCM shall meet all requirements of this FCP.

12.2.2.2 Welds. All welds to FCMs, except for those to bearing sole plates, shall be considered fracture critical and shall conform to the requirements of this FCP. Welds to compression members or compression areas of bending members shall not be defined as fracture critical.

12.3 Contract Documents

12.3.1 Prebid Designation of FCMs. All fracture critical members shall be identified on the plans, or otherwise described in the contract documents by the Engineer prior to bidding. Each FCM shall be individually designated. Each portion of a bending member that is fracture critical shall be clearly described giving the limits of the FCM. Within these limits, the provisions of 12.2.2 shall apply.

12.3.2 Shop Drawings. Shop drawings shall meet the requirements of 4.1.

12.3.2.1 Engineer's Review. The Engineer shall review all shop drawings to ensure that the Contractor has identified all FCMs. The Engineer shall check each shop drawing, including materials lists, for conformance with this FCP and the contract documents. WPSs for construction and repair are considered integral parts of shop drawings and shall be reviewed for acceptability. An indication of the Engineer's disposition of each drawing and procedure shall be shown by appropriate stamp, signature, and date.

12.3.2.2 Acceptance. The Contractor shall provide detailed shop drawings and WPSs for review by the Engineer, whose acceptance, or acceptance-as-noted, shall be required prior to fabrication. Such acceptance shall be limited to mean the reviewed material appears to conform to the intent of the contract documents (including this FCP). The Contractor shall be responsible for producing acceptable work.

12.4 Base Metal Requirements

12.4.1 Approved Base Metals. All steels described in 1.2.2 are approved for use in the construction of FCMs. Other steels may be approved by the Engineer.

12.4.2 Optional Base Metal Requirements. When the contract documents require heat treatment, toughness, chemical composition, or other provisions that are not part of AASHTO M 270M/M 270 (ASTM A709/A709M), or this FCP, these requirements shall be described in the mill order.

12.4.2.1 Optional Through-Thickness and Low-Sulfur Requirements. The Engineer may, when deemed necessary due to significant applied tensile stress in the through-thickness (Z) direction at specific locations in the structure, specify that individual plates shall have low sulfur (0.010% maximum) or improved throughthickness properties (20% reduction of area as described in ASTM A770/A770M), or both. Each plate required to have low sulfur and improved through-thickness properties shall be clearly identified on the plans. All requirements for such steels in addition to the requirements of this FCP shall be specified in the contract documents.

12.4.2.2 Optional Heat Treatment. The Engineer may order individual plates or parts to be normalized, or quenched and tempered, for special applications. All manufacturing requirements, such as forging, heat treatment, and testing requirements not part of the AASHTO material specifications, shall be clearly specified in the contract documents. The minimum CVN toughness values required at specific test temperatures shall be stated.

12.4.3 Base Metal Identification. When heat numbers and other identification markings are applied by die stamping, low-stress dies shall be used.

12.5 Welding Processes

12.5.1 Approved Processes. SMAW, SAW, FCAW, and GMAW with metal cored electrodes may be used to construct or repair FCMs.

12.5.2 Prohibited Processes and Procedure Restrictions. ESW and EGW shall be prohibited for welding FCMs. GMAW (except as allowed in 12.5.1) may only be used with the approval of the Engineer. When GMAW (except as allowed in 12.5.1) is allowed, qualification tests, procedure control and NDT shall be as specified by the Engineer.

12.5.3 Preferred Processes and Procedures. The Engineer may designate the use of specific processes, or process controls for specific bridge welds. All special provisions shall be specified in the contract documents. Other restrictions on the use of welding processes or procedures, if any, shall be described in the contract documents.

12.6 Consumable Requirements

12.6.1 Diffusible Hydrogen of Weld Metal

12.6.1.1 Electrode Optional Supplemental Diffusible Hydrogen—Designator Requirements for Welding. Electrodes and electrode/flux used to weld base metal with a minimum specified yield strength of 345 MPa [50 ksi] or less shall conform to the diffusible hydrogen requirements of the AWS filler metal specifications optional supplemental designator H4, H8, or H16. All electrodes and electrode/flux combinations used to weld base metal with a minimum specified yield strength greater than 345 MPa [50 ksi] shall conform to the diffusible hydrogen requirements of the AWS filler metal specification optional supplemental designator H4 or H8. This requirement does not apply to GMAW with solid electrodes approved per 12.5.2 for use on FCMs.

12.6.1.2 Special Requirements. Filler metal manufacturers shall specify any special precautions in excess of those contained in this FCP that are necessary to ensure the deposited weld metal shall meet the diffusible hydrogen limits of the specified classification when the consumables are removed from protective packaging and used without delay. Special storage provisions, maximum storage life, special handling and WPSs, if any, shall be completely described.

12.6.2 Weld Metal Strength and Ductility Requirements. Weld metal strength and ductility shall conform to the requirements of Table 7.3 unless otherwise provided in the contract documents.

12.6.3 Weld Metal Toughness Requirements

12.6.3.1 Matching Strength Groove Welds. Groove welds required to have a yield strength equal to the minimum specified yield strength of the base metal shall have a CVN test value equal to or exceeding that specified in Table 12.1.

12.6.3.2 Undermatching Strength Welds. All welds allowed to have undermatching yield strength shall have a minimum CVN test value of 34 J [25 ft·lb] @ –30°C [–20°F].

12.6.4 SMAW

12.6.4.1 SMAW Electrodes. All SMAW electrodes shall be manufactured, packaged in hermetically sealed containers, stored, transported, and delivered so that when removed from the container, the electrodes are undamaged and meet the diffusible hydrogen limits specified in 12.6.1.

SMAW electrodes used for tack welding as described in 12.13.1.2 on steel that is not preheated shall conform to the AWS filler metal specification's optional supplemental diffusible hydrogen designator H4. Electrodes classified with the optional R designator and E7018M electrodes may also be used for tack welding steel that is not preheated. Such electrodes shall have a coating moisture content consistent with the optional supplemental diffusible hydrogen designator H4.

12.6.4.2 Sealed Containers. Manufacturers' containers shall remain sealed until the electrodes are dispensed for work or are placed in heated storage as specified in 12.6.4.3. Containers shall be examined and if the hermetic seal was lost before opening, electrodes shall not be used for FCM welding. Electrodes shall be examined to ensure there is no damage that may adversely affect weld quality, including previously wet, contaminated, or broken coatings. Any electrodes with such defects in their usable length shall be discarded.

12.6.4.3 Storage. After removal from the manufacturer's sealed container, electrodes not immediately dispensed for use shall be continuously stored in an electrically heated, thermostatically controlled ovens at a minimum temperature of 120°C [250°F] until dispensed for use in the work. If the temperature falls below 120°C [250°F], electrodes shall be dried or redried per 12.6.4.4.

12.6.4.4 Drying Temperatures. As used here, the terms dried and drying are defined as holding electrodes at a specified temperature for a minimum period of time (below) or according to the manufacturer's requirements. Unless the manufacturer stipulates otherwise based on testing, electrodes for base metal with a specified minimum yield strength of 345 MPa [50 ksi] or less shall be dried at 230°C–290°C [450°F–550°F] for a minimum period of four hours, and electrodes for matching higher strength base metal shall be dried at 425°C–540°C [800°F–1000°F] for two hours. The terms redried and redrying are defined as drying a second time, whether the initial drying followed exposure or was based on manufacturer's requirements. If the temperature inside the storage oven falls between 50°C [125°F] and 110°C [225°F] for a period of up to eight hours, or below 50°C [125°F] for up to four hours, electrodes that were not previously redried shall be dried or redried or shall not be used to weld FCMs. Electrodes in storage ovens exposed to temperatures below 120°C [250°F] and times beyond the limits described above, or that were previously redried shall not be used.

12.6.4.5 Storage and Drying Ovens. Electrode ovens shall be designed for the storage, segregation, and drying of electrodes and shall be capable of maintaining a specified temperature between 120°C–290°C [250°F–550°F]. Each oven shall have a thermally sealed, latching door that is closed when not charging or discharging electrodes. To regularly verify the inside temperature without opening the door, each oven shall have either instrumentation allowing direct reading or a small port through which a thermometer can be inserted. Such ports shall be closed when not in use. Regardless of type, all oven temperature sensors shall be verified at least once per year.

12.6.4.6 Maximum Atmospheric Exposure of SMAW Electrodes. Except as provided in 12.6.4.8, SMAW electrodes exposed to the atmosphere for periods of time greater than those specified in Table 6.6 shall be dried or redried, or shall not be used to weld FCMs as stipulated in 12.6.4.7 or 12.6.4.9.

12.6.4.7 Electrode Exposure Limits. E70XX and E80XX-X electrodes not designated moisture resistant that are exposed up to but not exceeding the time limit of Table 6.6, and moisture resistant electrodes exposed up to but not exceeding the time limits in 12.6.4.8, may be dried or redried and then either returned to continuously heated storage or dispensed for use in the work. Electrodes shall not be redried more than once.

12.6.4.8 Optional Supplemental Moisture-Resistant Designators. Prior to drying, electrodes with the AWS filler metal specifications optional supplemental moisture resistance designator "R" may be exposed to the atmosphere for up to nine hours when welding steels with a specified minimum yield strength of 345 MPa [50 ksi] or less. After drying or redrying, these electrodes shall be governed by the exposure limits in Table 6.6. Moisture-resistant electrodes and their containers shall bear the additional designator "R". Electrodes shall not be redried more than once.

12.6.4.9 Electrodes for Grades HPS 485W [HPS 70W], HPS 690W [HPS 100W] Steels. Electrodes for matching strength welds on Grade HPS 485W [HPS 70W] and HPS 690W [HPS 100W] steels shall be used within the maximum atmospheric exposure limits of Table 6.6. When such electrodes' exposure exceeds Table 6.6 limits by less than one hour, they shall be dried or redried before being returned to heated storage or dispensed for use. Matching strength electrodes exposed more than one hour beyond Table 6.6 limits shall not be used for FCM welds. E70XX and E80XX electrodes for undermatched welds shall follow the requirements of 12.6.4.7. Electrodes shall not be redried more than once.

12.6.4.10 Production Welding Electrode Usage. Electrodes removed from heated storage shall be dispensed directly to welders for immediate use. They shall be kept in containers that protect them from contamination by moisture, oil, grease, and other sources of hydrogen, until used. The containers (scabbards) may be open at the top. Welders shall not be given more electrodes than can be used within the exposure limits allowed by this FCP.

12.6.5 SAW

12.6.5.1 Electrode and Flux Packaging. Electrodes shall be received in packaging that protects the electrode and coatings, if present, from damage. When removed from protective packaging and installed on machines, care shall be taken to protect the electrodes and coatings, if present, from deterioration or damage. No one shall modify or lubricate an electrode after manufacture for any reason. Flux shall be received in moisture-resistant packaging, transported and stored in a manner that will preserve the original manufactured condition. Flux from containers and packages that have been broken or opened prior to use shall not be used to weld FCMs.

12.6.5.2 Flux Handling and Drying (Baking). All of the contents of each container of SAW flux shall be placed in an approved storage and drying oven directly upon opening the flux to the atmosphere. All flux shall be baked at 290°C [550°F] minimum for at least two hours, or as recommended by the manufacturer, and then stored continuously at 120°C [250°F] minimum until dispensed for use. Hot make-up flux may be carried to machines in steel pails and stored at the point of welding for up to four hours, provided the flux is protected from contamination by an appropriate cover.

12.6.5.3 Drying and Storage Temperatures. Flux drying and storage ovens shall be electrically heated and thermostatically controlled to provide temperatures of 120°C–290°C [250°F–550°F]. Flux ovens shall be capable of drying and storing flux without causing a breakdown in particle size or segregation of components. Openings for charging and discharging of flux shall be closed when not in use. Each oven shall have a small port that may be opened briefly to insert a thermometer to measure the temperature of the oven without opening the door. The port shall be kept shut when not in use. Alternatively, ovens may be furnished with thermometers that allow direct reading of the inside temperature without opening the oven.

12.6.5.4 Discharge and Refill of Flux Hoppers. Welding machine flux hoppers and pressure containers shall be emptied of flux, entrapped fines and other particles, each time welding is suspended for 10 hours or more. Just prior to the resumption of welding, the hoppers and containers shall be refilled with new, properly dried flux taken directly from a storage or baking oven.

12.6.5.5 Open Top Flux Systems. When open top, hopper-type flux systems have not been refilled, or welding has been suspended for six hours, the top 10 mm [3/8 in] of flux in the hopper shall be removed and appropriate make-up flux added before welding is resumed.

12.6.5.6 Time Limits for Flux Replacement. The time limits of 12.6.5.4 and 12.6.5.5 may be extended based upon the results of tests acceptable to the Engineer. Tests conducted to demonstrate that the diffusible hydrogen limits of this FCP can be met without replacing flux as required by the referenced subclauses shall include, as a minimum, a description of the welding and flux-handling system, the relative humidity during testing, and the results of mercury or gas chromatograph diffusible hydrogen tests conducted in conformance with AWS A4.3. To be acceptable, diffusible hydrogen tests after extended time without replacement shall conform to the requirements of the optional diffusible hydrogen designator of the filler metal and flux being used.

12.6.5.7 Pneumatic Flux Delivery Systems. Compressed air used in pneumatic flux delivery systems shall be effectively filtered and dried to remove moisture, oil, rust and other contaminants. Dryers, unless automatically drained, shall be manually drained daily to ensure proper operation. Air lines shall be checked by venting the line to the atmosphere away from the work whenever the pressure container is refilled to verify the air is clean and dry.

12.6.5.8 Flux Recovery. Unfused flux may be recovered from clean base-metal surfaces and reused as described in 6.8.3. Flux may be recovered directly back into welding machine flux containers, provided it is recovered within a maximum of five minutes of being deposited on the steel. Flux recovered within a maximum of one hour may be returned to a flux drying oven. Flux exposed to the atmosphere for more than one hour after welding, and all flux that cannot be recovered from clean, dry, metal surfaces, shall be discarded. Recovered flux to be redried shall be held at a temperature of 290°C [550°F] minimum for at least two hours, or as recommended by the manufacturer, before reuse.

12.6.5.9 Recovered Flux. When flux is recovered, at least one third of the total flux used in welding shall be properly dried new flux. It shall be added in a way that will ensure mixing with the recovered flux in conformance with 6.8.3. A written description of the Contractor's flux recovery procedure shall be available for examination by welders and Inspectors.

12.6.5.10 Gravity Feed Delivery Systems. Operators of welders with gravity feed flux delivery systems may return flux directly back to the hopper during welding as provided in 12.6.5.8. During welding, properly dried new make-up flux representing at least 1/3 of the total volume shall be added at least hourly as welding progresses.

12.6.6 FCAW and GMAW Electrodes

12.6.6.1 Electrode Packaging. FCAW and GMAW (metal cored) electrodes shall be received in moisture resistant packages that are undamaged. They shall be protected against contamination and injury during shipment and storage. Electrode packages shall remain effectively sealed against moisture until the electrode is required for use. When removed from protective packaging and installed on machines, care shall be taken to protect the electrodes and coatings, if present, from deterioration or damage. No one shall modify or lubricate an electrode after manufacture for any reason except that drying may be used when recommended by the manufacturer.

12.6.6.2 Shielding Gas. Any shielding gas or gas mixture qualified as described in 7.12 may be used. The manufacturer shall provide certification that the gas or gas mixture conforms to the requirements of 6.12.

12.6.6.3 Electrode Storage. When welding is to be suspended for more than 8 hours, cored electrodes shall be removed from the machines and stored in airtight coverings or placed in a storage oven maintained at a temperature between 120°C and 290°C [250°F and 550°F] based on recommendations by the manufacturer.

Cored electrodes not consumed before accumulating 24 hours of exposure outside sealed or heated storage shall either be redried once as described in 12.6.6.5 or not be used for FCM welding. Electrode support shall be identified to facilitate monitoring of total atmospheric exposure time.

12.6.6.4 Time Limit Extension for Electrode Exposure. The time limits of 12.6.6.3 may be extended based on the results of tests acceptable to the Engineer. Tests conducted to demonstrate that the diffusible hydrogen limits of this FCP can be met at periods of exposure greater than specified in 12.6.6.3 shall include, as a minimum, a description of the maximum electrode atmospheric exposure time, the relative humidity during electrode exposure and weld testing, and the results of mercury or gas chromatograph diffusible hydrogen tests conducted in conformance with AWS A4.3. To be acceptable, diffusible hydrogen tests after extended exposure shall conform to the requirements of the optional supplemental diffusible hydrogen designator for the filler metal specified.

12.6.6.5 Drying Temperatures. When approved by the manufacturer, FCAW and GMAW (metal cored) electrodes on metal supports may be dried once at 260°C–290°C [500°F–550°F] for a minimum four hours, or as otherwise specified by the manufacturer in writing, to restore their condition. If the electrode or the electrode support is damaged by baking, the electrode shall not be used to weld FCMs.

12.7 Welding Procedure Specification (WPS)

Filler metals and fluxes used for WPS qualification testing shall not be subject to the diffusible hydrogen requirements of this Clause, provided the WPS and PQR show the same manufacturer's brand and type of filler metal and flux was used.

12.7.1 Limited Prequalification for SMAW. WPSs using SMAW electrodes classified as E7016, E7018, E7018-1 and E8018-X, including those with the "C" alloy and "M" military classifications and the optional supplemental designator "R" designating moisture resistance, shall be prequalified and exempt from WPS qualification test. All WPSs using other SMAW electrodes shall be qualified by tests as described in Clause 7 in addition to the tests performed by the manufacturer for electrode classification.

12.7.2 Groove WPS Qualification. Except as provided in 12.7.1, groove WPSs shall be qualified by testing in conformance with Clause 7. CVN test values shall be as specified in 12.6.3.

12.7.3 Fillet WPS Qualification. Except as provided in 12.7.1, fillet WPSs shall be qualified by groove weld testing in conformance with Clause 7.

12.7.4 Period of Effectiveness. When a specific Contractor has not previously performed production welding in accordance with a WPS qualified in accordance with this FCP, the required tests shall be completed within one year prior to the start of production welding. All subsequent tests shall be conducted at a frequency that will ensure no groove weld PQR used as a basis for preparation of WPSs is more than 60 months old. There is no limit to the period of effectiveness for fillet weld soundness tests.

12.8 Certification and Qualification

Contractors shall be certified under the AISC (American Institute of Steel Construction) Certification Program for Steel Bridge Fabricators with the Fracture Critical supplement, or an equivalent program acceptable to the Engineer.

12.8.1 Welding Personnel Qualification. All welders, including welding operators and tack welders, shall be qualified by test within 6 months before beginning production welding or shall be requalified on an annual basis. Upon beginning work on a Fracture Critical project, the qualification of a welder or welding operator shall be considered valid until the project is completed provided the welder or welding operator meets the continuity requirements of 7.21.4. For welders and welding operators performing Fracture Critical CJP groove welds, initial qualification shall be based on acceptable results of both mechanical (bend) tests and radiography as described in Clause 7, Part B. Welders and welding operators performing Fracture Critical fillet welding shall be qualified based on acceptable results of Clause 7, Part B. Tack welders shall be qualified as described in Clause 7, Part B. Annual requalification may be based upon acceptable results of radiography of production groove welds (for CJP groove welders) or test plates as approved by the Engineer.

12.9 As-Received Inspection of Base Metal

All base-metal surfaces and edges shall be visually inspected for discontinuities. The standards for visual acceptance of shape, plate, and bar-rolled surfaces shall be as described in ASTM A6/A6M unless otherwise provided in the contract documents.

12.10 Thermal Cutting

Edges and ends of plates for FCMs shall be cut to size by thermal cutting. Universal mill and sheared plates shall have a minimum of 5 mm [3/16 in] of material removed from rolled or sheared edges and from ends by thermal cutting prior to assembly and welding. This provision shall not apply to edges of bars and shapes as defined in ASTM A6/A6M, or the ends of stiffeners and connection plates where there is no calculated tensile stress.

12.10.1 Thermal-Cut Edge Requirements. Thermal-cut edges (TCEs) shall meet the requirements of 5.2 unless otherwise specified in the contract documents.

12.10.2 Magnetic Particle Testing (MT). Visually-detected discontinuities shall be inspected further using the Yoke method of MT described in 8.7.8.2.

12.10.3 Laminar Discontinuities. Laminar discontinuities shall be addressed in accordance with 5.2.6, except that for visible discontinuities at joint faces or plate edges within 300 mm [12 in]. of groove welds in butt joints subject to calculated tensile stress normal to the weld axis, Table 12.2 shall apply in lieu of Table 5.1. Any repair welds to address laminar discontinuities in fracture-critical members shall be performed in accordance with 12.17.

12.10.4 Allowable Discontinuities. Except as provided in 12.10.3, base metal at the fusion face of butt, T-, and corner joints may have discontinuities allowed by 5.2. Repair welding, if any, shall be done in conformance with 12.17.3. Excavated, or repaired, surfaces shall be finished to produce conditions suitable for final welding.

12.11 Repair of Base Metal

Base metal discontinuities adjacent to fracture-critical butt joints as described in 12.10.3 shall be repaired or replaced by the Contractor in conformance with the following options:

12.11.1 Rotation of Base Metal. The base metal may be rotated end for end when it is possible to remove discontinuities from areas designated as a FCM.

12.11.2 Thermal Cutting. When the unacceptable discontinuities are localized, these may be removed by thermal cutting to sound metal, reducing the length of the effected plate, bar, or shape. This requires adjacent pieces of steel to be extended beyond their detailed length and mandates relocation of the affected butt joint. Relocation of butt welds from their detailed location shall require approval by the Engineer. All changes in weld location shall be recorded on the shop drawings.

12.11.3 Repairs. Repairs may be made by welding as described in 12.17.

12.11.4 Replacement. With the Engineer's approval, the Contractor may remove a defective portion of the base metal and replace it with new material of the same or greater strength, toughness, and corrosion resistance, except Grades HPS 485W [HPS 70W] and HPS 690W [HPS 100W] shall not be substituted for lower strength steels. Replacement steel and welds necessary to affect the base-metal substitution shall conform to all requirements of the FCP. Unless otherwise approved by the Engineer, the minimum replacement length shall be 1.5 m [5 ft]. All base metal replacements shall be recorded in the inspection records and shop drawings.

12.12 Straightening, Curving, and Cambering

Straightening, curving, and cambering shall be in accordance with 5.7.3. Base metal and weld metal that is sharply bent or kinked shall be rejected and replaced.

12.13 Tack Welds and Temporary Welds

12.13.1 Tack Welds

12.13.1.1 Location. All tack welds used in assembly shall be located within the joint unless otherwise approved by the Engineer.

12.13.1.2 Requirements. All tack welds shall meet the requirements of Table 12.3, or shall be removed as described in 12.13.3.

12.13.2 Temporary Welds. All welds not shown as permanent welds on the drawings or approved by the Engineer shall be removed as described in 12.13.3.

12.13.3 Weld Removal. When required, weld removal shall include all of the weld plus 3 mm [1/8 in] of the adjacent base metal to remove the HAZ. Weld and base metal removal sites shall be faired to adjacent surfaces on a slope not steeper than 1 into the metal to 10 along the surface. The surface roughness shall not exceed 3 µm [125 µin].

12.14 Preheat and Interpass Temperature Control

Preheat and interpass temperature control shall be as specified in 6.2. The minimum preheat and interpass temperature for AASHTO M 270M/M 270 (ASTM A709/A709M) Grade 250 [36], 345 [50], 345S [50S], 345W [50W], HPS 345W [HPS 50W], and Grade HPS 485W [HPS 70W] steels shall be as described in Tables 12.4, 12.5, 12.6, and 12.7. The minimum and maximum preheat temperatures for M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W] steel shall be as described in Table 12.8. For Grade HPS 485W [HPS 70W], the maximum preheat and interpass temperature shall be 230°C [450°F] for all thicknesses.

12.15 Postweld Thermal Treatments

12.15.1 Hydrogen Diffusion Postheat. Hydrogen diffusion postheat shall be required when specified by this code, the contract documents, WPS, or repair procedure

12.15.1.1 Minimum Temperature Prior to Hydrogen Diffusion Postheat. When hydrogen diffusion postheat is required, the weld shall not be allowed to cool below the minimum preheat and interpass temperature before being raised to the postheat temperature.

12.15.1.2 Hydrogen Diffusion Postheat Temperature Limitations. When hydrogen diffusion postheat is required, welds and adjacent base metal shall be heated to a temperature of 230°C [450°F] minimum to 315°C [600°F] maximum for not less than one hour for each 25 mm [1 in] of weld thickness, or two hours, whichever is less. The minimum heating time for repair welds shall be one hour for each 25 mm [1 in] of repair weld depth from the surface, but not less than one hour. Longer heating periods may be used.

12.15.2 Postweld Heat Treatment (PWHT). Any heating of welds or base metal by sources other than the welding arc to temperatures in excess of 480°C [900°F] except for brief periods required for approved heat curving, cambering and straightening, shall be considered PWHT.

12.15.2.1 Approval. All PWHT shall be approved by the Engineer. A detailed procedure listing all PWHT control items, including those in 12.15.2.2, shall be submitted to the Engineer for approval.

12.15.2.2 Controls. PWHT shall be completely described giving details of minimum and maximum temperature, maximum heating and cooling rates, minimum and maximum time at specified temperatures, and all other details necessary to control the heat treatment.

12.15.2.3 Testing. Tests shall be performed before and after heating to determine the effects of the proposed heat treatment on the strength, ductility, and toughness of welds and base metal. Test plates shall receive the same heat treatment as that proposed before test specimens are removed by machining. Test specimens removed from heat-treated welds shall not be reheated for any purpose. Test results shall be submitted to the Engineer for approval. The Engineer may accept records of previous qualification tests in lieu of testing. MT and UT, when required, shall be repeated or performed after the weldment has cooled to ambient temperature.

12.16 Weld Inspection

All welds, including repair welds, shall be inspected as required by Clause 8 and shall meet the additional requirements of this FCP.

12.16.1 QA/QC. The Engineer shall provide QA inspection as necessary to verify the proper and sufficient implementation of this FCP and applicable provisions of the contract documents. QA inspection by the Engineer shall not relieve the Contractor from the responsibility to conform to all requirements of the contract documents, including the requirement to provide inspection and tests as described in Clause 8 and this FCP.

12.16.1.1 Inspectors. Inspectors shall be qualified as specified in 8.1.3. Lead Inspectors shall have a minimum of three years experience in steel bridge fabrication inspection. A Lead Inspector shall be defined as the leader of their inspection team at a specific work location, one who assigns other Inspectors as necessary and supervises their work. The Lead Inspector shall be familiar with and shall have seen each FCM that he or she has inspection responsibility for and may accept as described in 12.16.5.2. Each Inspector shall have the authority to accept or reject materials and workmanship subject to review by the Lead Inspector.

12.16.1.2 NDT Technicians. NDT technicians shall be certified to Level II or certified to Level III and qualified to perform as a Level II in conformance with ASNT's *Recommended Practice No.* SNT-TC-1A. Level II technicians shall be supervised by an individual certified to Level III. Level III individuals shall possess a currently valid ASNT Level III certificate. The Engineer may accept alternative qualifications that are deemed equivalent.

12.16.2 Type of Weld and NDT Required

12.16.2.1 Tension and Repaired Welds in Butt Joints. Butt joints in tension and repaired groove welds in butt joints shall be inspected by both RT and UT.

12.16.2.2 T- and Corner Joint Tension and Repaired Groove Welds. All tension and repaired groove welds in T- and corner joints shall be inspected by UT.

12.16.2.3 Fillet Weld Repairs. Fillet weld repairs shall be inspected by MT. The test length shall include 100% of the length of the repair, and, when appropriate, at least 300 mm [12 in] beyond the ends of each repair weld.

12.16.3 RT Requirements. RT shall be done using hole-type IQIs as described in Table 8.2 and Figure 8.1E.

12.16.4 Cooling Times Prior to Inspection. RT and preliminary visual inspections may be performed as soon as welds have cooled. UT, MT, and final visual inspection shall be done after the welds have cooled to ambient temperature for at least the following minimum time periods:

(1) Fillet welds on steel with a minimum specified yield strength of 345 MPa [50 ksi] or less: 24 hours.

(2) Fillet welds on steel with a minimum specified yield strength greater than 345 MPa [50 ksi]: 48 hours.

(3) Groove welds in steel with a minimum specified yield strength of 345 MPa [50 ksi] or less: 24 hours when the weld depth is 50 mm [2 in] or less, and 48 hours when the weld depth is greater than 50 mm [2 in].

(4) Groove welds in steel with a minimum specified yield strength greater than 345 MPa [50 ksi]: 48 hours when the weld depth is 50 mm [2 in] or less and 72 hours when the weld depth is greater than 50 mm [2 in].

12.16.5 Inspection and Record Keeping

12.16.5.1 Certified Reports. Certified copies of mill test reports, visual and NDT reports, radiographs and other documentation that materials and workmanship conform to the requirements of the contract documents shall be available for examination and shall be included in the permanent record. The Contractor shall verify that all fracture-critical base metal is identified with mill test reports satisfying contract requirements. Heat and mill test report identity shall be maintained when base metal is cut for use in other FCMs. All repairs requiring documentation as described in 12.17.3 shall be recorded in the inspection records. The inspection record of each fracture critical erection piece shall be identified by the erection mark specified in the shop drawings.

12.16.5.2 Identification of Inspectors. All Inspectors who have inspected FCMs shall be identified in the inspection records. The QC Lead Inspectors that have inspected the FCM, reviewed the inspection records and performance of assistant Inspectors, and determined that the FCM meets the requirements of this FCP and the contract documents shall sign and date the inspection record noting their acceptance.

12.16.5.3 Recording Discontinuities Found by UT. All discontinuities found by UT must be recorded on the NDT report if required in 8.19.8.

12.17 Repair Welding

Repair welding shall be defined as any welding, including removal of weld or base metal in preparation for welding, necessary to correct unacceptable discontinuities in materials or workmanship. Welded repairs shall be categorized as noncritical (see 12.17.2) or critical (see 12.17.3), with separate requirements for each.

12.17.1 WPS Requirements. Repair welding shall be done in conformance with an approved WPS. The WPS may be preapproved as described in 12.17.2.1, or individually approved as described in 12.17.4.

12.17.1.1 Approval Procedure. The Contractor may prepare procedures, including WPSs, for the repair of anticipated routine problems and submit them to the Engineer for approval before beginning the work. The Contractor may use preapproved repair procedures as soon as the QA Inspector has verified the defect to be repaired is covered by the procedure.

12.17.1.2 Drawings. Repair WPSs shall include sketches, or full-size drawings, as necessary to describe the unacceptable discontinuity and the proposed method of repair. WPSs for critical repairs described in 12.17.3 shall document the location of the unacceptable discontinuities to be repaired.

12.17.1.3 Location. Unacceptable discontinuities to be repaired shall be shown in plan view, elevation, and section as necessary to describe the discontinuity prior to repair. The drawings shall be revised, if necessary, at the completion of repairs to document differences between the presumed initial type, size, orientation, and location of the unacceptable discontinuity and the final complete description of the unacceptable discontinuity as observed and measured during repair.

12.17.2 Noncritical Repair Welds. Noncritical repair welds are generally welds that deposit additional weld beads or layers to compensate for insufficient weld size and to fill limited excavations to remove unacceptable edge or surface discontinuities, rollover or undercut, including:

(1) Gouges in cut edges that are 10 mm [3/8 in] deep, or less.

(2) Laminar discontinuities less than 25 mm [1 in] deep, or with a depth less than one-half the thickness of the cut edge, whichever is less, provided the discontinuity is not within 300 mm (12 in] of a butt joint loaded in tension. Repair shall be made by excavating from the cut edge.

(3) Repair of base-metal surfaces as provided in ASTM A6/A6M.

(4) First-time excavation and repair from one side of groove welds and fillet welds containing unacceptable porosity, slag and fusion discontinuities, provided the excavations do not exceed the following limits:

Length of Weld "L"	Length of Excavation
Up to 0.5 m [1-1/2 ft]	L or 250 mm [10 in], whichever is less
Over 0.5 m [111/2 ft] to 1.0 m [3 ft]	300 mm [1 ft]
Over 1.0 m [3 ft] to 2.0 m [6 ft]	450 mm [1-1/2 ft]
Over 2.0 m [6 ft] to 4.0 m [12 ft]	600 mm [2 ft]
Over 4.0 m [12 ft] to 8.0 m [24 ft]	900 mm [3 ft]
Over 8.0 m [24 ft]	900 mm [3 ft] or 10% L, whichever is greater

The depth of groove weld excavation shall not exceed 65% of the weld size shown on the drawings.

(5) Repairs to cracks confined to root passes discovered and corrected before depositing subsequent weld passes.

(6) Repairs to ends of members where there is no deadload or liveload stress.

(7) Deposition of weld metal up to 10 mm [3/8 in] deep, or 1/4 the base metal thickness, whichever is less, to correct for length or joint geometry.

12.17.2.1 Noncritical Repair Procedures. Provision shall be made for the preapproval and use of noncritical repair procedures and WPSs to ensure that the Contractor has an acceptable plan for routine repairs prior to beginning the work.

12.17.3 Critical Weld Repairs. Except as provided in 12.17.2, all welded repairs shall be considered critical. They include, but are not limited to the following:

(1) Repair of gouges in cut edges greater than 10 mm [3/8 in] deep.

(2) Repair of laminar discontinuities, except as provided in 12.17.2(2). Repair may be made from the cut edge, or from a surface, as approved by the Engineer.

(3) Repair of surface or internal discontinuities in rolled, forged, and cast products not covered by 12.17.2(3).

(4) Repair of cracks in base metal and welds including lamellar tears except as provided in 12.17.2(5).

(5) Corrections requiring weld removal and rewelding except as provided in 12.17.2(4).

(6) All welding to correct errors in fabrication such as improper cutting, punching, drilling, machining, assembly, etc.

12.17.4 Approval. All critical repairs to base metal and welds shall be approved by the Engineer prior to beginning the repair and shall be documented giving details of the type of discontinuity and extent of repair.

12.17.5 Inspection. All repair welding shall be subject to QC and QA inspection.

12.17.6 Repair Procedure Minimum Provisions. Noncritical repairs described in 12.17.2 need not be recorded, except that locations of first time excavations and repairs per 12.17.2(4) shall be temporarily recorded in case a second, critical repair is required. All other repair WPSs shall include at least the following provisions described in the order in which the work will be performed:

(1) Surfaces shall be cleaned as necessary to facilitate visual inspection and NDT so that QC and QA Inspectors can accurately characterize the discontinuity(ies) of concern. Surfaces shall be finished as necessary to facilitate visual inspection and NDT.

(2) Unacceptable discontinuities to be repaired shall be recorded as required by 12.17.1.3, and in addition, the location of the excavation and proposed repair to edges, ends, holes, welds and other details of the FCM shall be shown.

(3) The preheating temperature prior to air carbon arc gouging shall be described in the WPS. Preheat for gouging shall not be less than 65°C [150°F].

(4) The method and extent of excavation to remove unacceptable weld and base metal discontinuities shall be completely described, and when appropriate, shall include the sequence of progressive excavations.

(5) MT and other NDT, if ordered by the Engineer, shall be used to verify that all of the unacceptable discontinuity is removed.

(6) All thermal cut and gouged surfaces that shall be welded on shall be ground to produce a smooth, bright surface. Oxygen gouging shall be prohibited.

(7) All temporary weld extensions and steel backing, including the method of attachment, shall be shown in detail.

(8) Preheat and interpass temperature controls shall be listed. They shall meet, or exceed, the following minimum requirements:

(a) All steels with a minimum specified yield strength of 485 MPa [70 ksi] or less, in thicknesses up to 40 mm [1-1/2 in] inclusive, shall have a minimum preheat and interpass temperature of 160°C [325°F]. For thicknesses greater than 40 mm [1-1/2 in], the minimum preheat and interpass temperature shall be 200°C [400°F].

(b) Grade HPS 690W [HPS 100W] steel shall have a preheat and interpass temperature that conforms to the requirements of Table 12.8 for the heat input used, except that the minimum temperature shall be 110°C [225°F]. Care shall be taken when welding Grade HPS 690W [HPS 100W] steel to ensure that the combined preheat or interpass temperature plus welding heat input does not exceed the manufacturer's recommendations.

(9) Welding shall be done as described in the approved repair procedure. WPSs qualified for welding of FCMs need not be requalified for repair welding, provided the joint detail used allows access for welding.

(10) Peening, if required, shall be listed in the repair procedure and shall conform to the requirements of 5.8. Any additional requirements shall be completely described.

(11) Repair welds in groove excavations greater than 12 mm [1/2 in] deep shall receive hydrogen diffusion postheat as described in 12.15.1. Hydrogen diffusion postheat, when required, shall be as described in the repair procedure.

(12) Repaired surfaces shall be finished flush with adjacent base metal or weld surfaces, or finished with slight reinforcement that is faired to adjoining surfaces as approved by the Engineer.

(13) PWHT, when required, shall be described in the repair procedure and shall conform to the requirements of 12.15.2.

Table 12.1
CVN Test Values of Weld Metal with Matching Strength (see 12.6.3.1)

M 270 M/M 270 (A709/A709M) Steel Grades	Minimum CVN Test Energy, J [ft·lb]	Test Temperature
250 [36]	34 [25]	–30°C [–20°F]
345 [50], 345S [50S]	34 [25]	–30°C [–20°F]
345W [50W], HPS 345W [HPS 50W]	34 [25]	–30°C [–20°F]
HPS 485W [HPS 70W]	41 [30]	–30°C [–20°F]
HPS 690W [HPS 100W]	48 [35]	–35°C [–30°F]

Table 12.2
Limits on Acceptability and Repair of Cut Edge Discontinuities of Material (see 12.10.3)

Description of Discontinuity	Plate Repair Required
Any discontinuity with depth not greater than 6 mm [1/4 in]	Remove, need not weld
Any discontinuity with depth over 6 mm [1/4 in] but not greater than 25 mm [1 in]	Remove and weld Aggregate length of welding shall not exceed 20% of the length of material edge being repaired
Any discontinuity with depth greater than 25 mm [1 in]	See 5.2.6.7

Table 12.3
Tack Weld Requirements (see 12.13.1.2)

Type	WPS Required?	Minimum Size	Minimum Length	Minimum Preheat	Notes
Remelted by SAW	No	None	None	None	a, b
Covered by non-SAW	Yes	Table 4.1 or 4.2	75 mm [3 in]	Table 12.4, 12.5, 12.6, 12.7, or 12.8	
Tack welds outside joint	Yes	Table 4.1 or 4.2	75 mm [3 in]	Table 12.4, 12.5, 12.6, 12.7, or 12.8	c
Tack welds <75 mm [3 in] long, or smaller than Table 4.1 or 4.2	Yes	None	None	200°C [400°F]	

[a] GMAW may be used for tack welding without the Engineer's approval.
[b] SMAW electrodes shall meet the diffusible hydrogen requirements of 12.6.4.1.
[c] Tack welds outside the joint shall require the Engineer's approval (see 12.13.1.1).

Note: Filler metals listed in Table 6.1 shall be used.

Table 12.4
M270M (A709M) Gr. 250, 345, 345S
Minimum Preheat and Interpass Temperatures, °C (see 12.14)

	Heat Input (as calculated by 7.12) kJ/mm								
	1.2 < HI ≤ 2.0			2.0 < HI ≤ 2.8			H > 2.8		
Thickness t, in	H4	H8	H16	H4	H8	H16	H4	H8	H16
t ≤ 20	40	50	70	40	40	50	40	40	40
20 < t ≤ 40	70	80	100	50	70	80	40	50	70
40 < t ≤ 60	90	110	120	80	90	110	70	80	90
t > 60	150	160	180	140	150	160	120	140	150

Table 12.5
M270 (A709) Gr. 36, 50, 50S
Minimum Preheat and Interpass Temperatures, °F (see 12.14)

	Heat Input (as calculated by 7.12) kJ/in								
	30 < HI ≤ 50			50 < HI ≤ 70			H > 70		
Thickness t, in	H4	H8	H16	H4	H8	H16	H4	H8	H16
t ≤ 3/4	100	125	150	100	100	125	100	100	100
3/4 < t ≤ 1-1/2	150	175	200	125	150	175	100	125	150
1-1/2 < t ≤ 2-1/2	200	225	250	175	200	225	150	175	200
t > 2-1/2	300	325	350	275	300	325	250	275	300

Table 12.6
M270M (A709M) Gr. 345W, HPS 345W, HPS 485W
Minimum Preheat and Interpass Temperatures, °C (see 12.14)

	Heat Input (as calculated by 7.12) kJ/mm								
	1.2 < HI ≤ 2.0			2.0 < HI ≤ 2.8			H > 2.8		
Thickness t, in	H4	H8	H16	H4	H8	H16	H4	H8	H16
t ≤ 20	40	50	70	40	40	50	40	40	40
20 < t ≤ 40	90	110	120	80	90	110	70	80	90
40 < t ≤ 60	150	160	180	140	150	160	120	140	150
t > 60	180	190	200	160	180	190	150	160	180

Table 12.7
M270 (A709) Gr. 50W, HPS 50W, HPS 70W
Minimum Preheat and Interpass Temperatures, °F (see 12.14)

	Heat Input (as calculated by 7.12) kJ/in								
	30 < HI ≤ 50			50 < HI ≤ 70			H > 70		
Thickness t, in	H4	H8	H16	H4	H8	H16	H4	H8	H16
t ≤ 3/4	100	125	150	100	100	125	100	100	100
3/4 < t ≤ 1-1/2	200	225	250	175	200	225	150	175	200
1-1/2 < t ≤ 2-1/2	300	325	350	275	300	325	250	275	300
t > 2-1/2	350	375	400	325	350	375	300	325	350

Table 12.8
M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W]
Minimum and Maximum Preheat/Interpass Temperature, °C [°F] (see 12.14)

	Heat Input (as calculated by 7.12) kJ/mm [kJ/in]				
Thickness t, mm [in]	1.2 [30] ≤ HI < 1.6 [40]	1.6 [40] ≤ HI < 2.0 [50]	2.0 [50] ≤ HI < 2.8 [70]	2.8 [70] ≤ HI < 3.6 [90]	3.6 [90] ≤ HI
6 [1/4] ≤ t ≤ 10 [3/8]	40–60 [100–150]	—	—	—	—
10 [3/8] < t ≤ 13 [1/2]	60–160 [150–300]	40–100 [100–200]	—	—	—
13 [1/2] < t ≤ 20 [3/4]	120–200 [250–400]	100–180 [200–350]	40–120 [100–250]	—	—
20 [3/4] < t ≤ 25 [1]	—	120–200 [250–400]	120–200 [250–400]	60–160 [150–300]	—
25 [1] < t ≤ 50 [2]	—	—	120–200 [250–400]	120–200 [250–400]	100–180 [200–350]
t > 50 [2]	—	—	150–240 [300–450]	140–240 [300–450]	140–240 [300–450]

Note: The table applies to electrodes with the H4 or H8 optional supplemental designator for diffusible hydrogen limits.

Annexes
Normative Information

These annexes are part of this standard and includes mandatory elements for use with this standard.

Informative Information

These annexes are not considered part of the standard and are provided for informational purposes.

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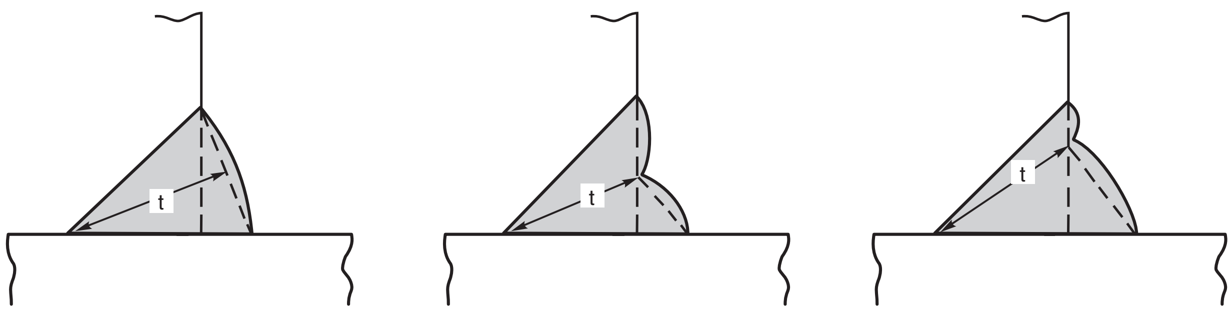
Annex A (Normative)
Effective Throat

This annex is part of this standard and includes mandatory elements for use with this standard.



Note: The effective throat of a weld is the minimum distance from the root of the joint to its face, with or without a deduction of 3 mm [1/8 in] as required by 4.3.1.3, less any convexity.

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Annex B (Normative)
Effective Throats of Fillet Welds in Skewed T-Joints

This annex is part of this standard and includes mandatory elements for use with this standard.

Table B.1 is a tabulation showing equivalent leg size factors for a range of dihedral angles between 60° and 135°, assuming there is no root opening. Root opening(s) 2 mm [1/16 in] or greater, but not exceeding 5 mm [3/16 in], shall be added directly to the leg size. The required leg size for fillet welds in skewed joints shall be calculated using the equivalent leg size factor for correct dihedral angle, as shown in the example.

Example

(SI Units)

Given: Skewed T-joint, angle: 75°; root opening: 2 mm [1/16 in]

Required: Strength equivalent to 90° fillet weld of size: 8 mm [5/16 in]

Procedure:
(1) Factor for 75° from Table B.1: 0.86
(2) Equivalent leg size, w, of skewed joint, without root opening:
W = 0.86 × 8 = 6.9 mm [1/4 in]
(3) With root opening of: 2.0 mm [5/64 in]
(4) Required leg size, W, of skewed fillet weld: [(2) + (3)] 8.9 mm [21/64 in]
(5) Rounding up to a practical dimension: w = 9.0 mm [5/16 in]

For fillet welds having equal measured legs (w_n), the distance from the root of the joint to the face of the diagrammatic weld (t_n) may be calculated as follows:

For root openings >2 mm [1/16 in] and ≤5 mm [3/16 in], use

$$S_n = \frac{W_n - R_n}{2 \sin \frac{\Psi}{2}}$$

For root openings <2 mm [1/16 in], use

$R_n = 0$ and $S'_n = S_n$

where the measured leg of such fillet weld (W_n) is the perpendicular distance from the surface of the joint to the opposite toe, and (R) is the root opening, if any, between parts (see Figure 4.3). Acceptable root openings are defined in 5.3.1.

Table B.1
Equivalent Fillet Weld Leg Size Factors for Skewed T-Joints, R = 0

Dihedral angle, Ψ	60°	65°	70°	75°	80°	85°	90°	95°
Comparable fillet weld size for same strength	0.71	0.76	0.81	0.86	0.91	0.96	1.00	1.03
Dihedral angle, Ψ	100°	105°	110°	115°	120°	125°	130°	135°
Comparable fillet weld size for same strength	1.08	1.12	1.16	1.19	1.23	1.25	1.28	1.31

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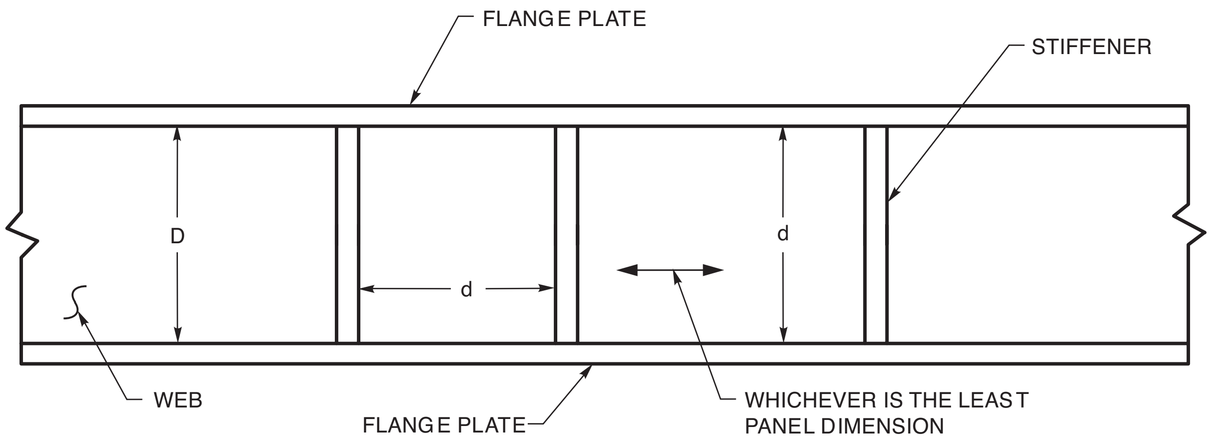
Annex C (Normative)
Flatness of Girder Webs—Bridges

This annex is part of this standard and includes mandatory elements for use with this standard.



Notes:
1. D = Depth of web.
2. d = Least panel dimension.

DIMENSIONS IN MILLIMETERS

Intermediate Stiffener on Both Sides of Web—Fascia Girders

Thickness of Web, mm	Depth of Web, mm	Least Panel Dimension, mm											
8	Less than 1200 1200 and over	780 630	1040 840	1050	1260	1470	1680	1890	2100	2310	2520	2730	2940
9	Less than 1350 1350 and over	780 630	1040 840	1300 1050	1260	1470	1680	1890	2100	2310	2520	2730	2940
10	Less than 1500 1500 and over	780 630	1040 840	1300 1050	1260	1470	1680	1890	2100	2310	2520	2730	2940
11	Less than 1650 1650 and over	780 630	1040 840	1300 1050	1560 1260	1470	1680	1890	2100	2310	2520	2730	2940
12	Less than 1800 1800 and over	780 630	1040 840	1300 1050	1560 1260	1470	1680	1890	2100	2310	2520	2730	2940
14	Less than 2100 2100 and over	780 630	1040 840	1300 1050	1560 1260	1820 1470	2080 1680	1890	2100	2310	2520	2730	2940
16	Less than 2400 2400 and over	780 630	1040 840	1300 1050	1560 1260	1820 1470	2080 1680	2340 1890	2100	2310	2520	2730	2940
		Maximum Allowable Variation, mm											
		6	8	10	12	14	16	18	20	22	24	26	28

Intermediate Stiffeners on One Side of Web Only—Fascia Girders

Thickness of Web, mm	Depth of Web, mm	Least Panel Dimension, mm											
8	Less than 800 800 and over	720 480	640	800	960	1120	1280	1440	1600	1760	1920	2080	2240
9	Less than 900 900 and over	720 480	640	800	960	1120	1280	1440	1600	1760	1920	2080	2240
10	Less than 1000 1000 and over	720 480	960 640	800	960	1120	1280	1440	1600	1760	1920	2080	2240
11	Less than 1100 1100 and over	720 480	960 640	800	960	1120	1280	1440	1600	1760	1920	2080	2240
12	Less than 1200 1200 and over	720 480	960 640	1200 800	960	1120	1280	1440	1600	1760	1920	2080	2240
14	Less than 1400 1400 and over	720 480	960 640	1200 800	960	1120	1280	1440	1600	1760	1920	2080	2240
16	Less than 1600 1600 and over	720 480	960 640	1200 800	1440 960	1120	1280	1440	1600	1760	1920	2080	2240
		Maximum Allowable Variation, mm											
		6	8	10	12	14	16	18	20	22	24	26	28

DIMENSIONS IN MILLIMETERS

Intermediate Stiffeners on Both Sides of Web—Interior Girders

Thickness of Web, mm	Depth of Web, mm	Least Panel Dimension, mm											
8	Less than 1200 1200 and over	690 550	920 740	1150 920	1100	1290	1470	1660	1840	2020	2210	2390	2580
9	Less than 1350 1350 and over	690 550	920 740	1150 920	1100	1290	1470	1660	1840	2020	2210	2390	2580
10	Less than 1500 1500 and over	690 550	920 740	1150 920	1380 1100	1290	1470	1660	1840	2020	2210	2390	2580
11	Less than 1650 1650 and over	690 550	920 740	1150 920	1380 1100	1610 1290	1470	1660	1840	2020	2210	2390	2580
12	Less than 1800 1800 and over	690 550	920 740	1150 920	1380 1100	1610 1290	1470	1660	1840	2020	2210	2390	2580
14	Less than 2100 2100 and over	690 550	920 740	1150 920	1380 1100	1610 1290	1840 1470	2070 1660	1840	2020	2210	2390	2580
16	Less than 2400 2400 and over	690 550	920 740	1150 920	1380 1100	1610 1290	1840 1470	2070 1660	2300 1840	2020	2210	2390	2580
		Maximum Allowable Variation, mm											
		6	8	10	12	14	16	18	20	22	24	26	28

Intermediate Stiffeners on One Side Only of Web—Interior Girders

Thickness of Web, mm	Depth of Web, mm	Least Panel Dimension, mm											
8	Less than 800 800 and over	600 400	800 540	670	800	940	1070	1210	1340	1470	1610	1740	1880
9	Less than 900 900 and over	600 400	800 540	670	800	940	1070	1210	1340	1470	1610	1740	1880
10	Less than 1000 1000 and over	600 400	800 540	1000 670	800	940	1070	1210	1340	1470	1610	1740	1880
11	Less than 1100 1100 and over	600 400	800 540	1000 670	800	940	1070	1210	1340	1470	1610	1740	1880
12	Less than 1200 1200 and over	600 400	800 540	1000 670	1200 800	940	1070	1210	1340	1470	1610	1740	1880
14	Less than 1400 1400 and over	600 400	800 540	1000 670	1200 800	1400 940	1070	1210	1340	1470	1610	1740	1880
16	Less than 1600 1600 and over	600 400	800 540	1000 670	1200 800	1400 940	1600 1070	1210	1340	1470	1610	1740	1880
		Maximum Allowable Variation, mm											
		6	8	10	12	14	16	18	20	22	24	26	28

No Intermediate Stiffeners—Interior and Fascia Girders

Thickness of Web, mm	Least Panel Dimension, mm												
Any	900	1200	1500	1800	2100	2400	2700	3000	3300	3600	3900	4200	
	Maximum Allowable Variation, mm												
	6	8	10	12	14	16	18	20	22	24	26	28	

DIMENSIONS IN INCHES

Intermediate Stiffeners on One Side Only of Web, Interior Girders

Thickness of Web, in	Depth of Web, in	Least Panel Dimension, in													
5/16	Less than 31 31 and over	25 17	31 21	25	29	34	38	42	46	50	54	59	63	67	71
3/8	Less than 38 38 and over	25 17	31 21	38 25	29	34	38	42	46	50	54	59	63	67	71
7/16	Less than 44 44 and over	25 17	31 21	38 25	44 29	34	38	42	46	50	54	59	63	67	71
1/2	Less than 50 50 and over	25 17	31 21	38 25	44 29	50 34	38	42	46	50	54	59	63	67	71
9/16	Less than 56 56 and over	25 17	31 21	38 25	44 29	50 34	56 38	42	46	50	54	59	63	67	71
5/8	Less than 63 63 and over	25 17	31 21	38 25	44 29	50 34	56 38	63 42	46	50	54	59	63	67	71
		Maximum Allowable Variation, in													
		1/4	5/16	3/8	7/16	1/2	9/16	5/8	11/16	3/4	13/16	7/8	15/16	1	1-1/16

Note: For actual dimensions not shown, use the next higher figure.

Intermediate Stiffeners on Both Sides of Web, Interior Girders

Thickness of Web, in	Depth of Web, in	Least Panel Dimension, in													
5/16	Less than 47 47 and over	29 23	36 29	43 35	50 40	46	52	58	63	69	75	81	86	92	98
3/8	Less than 56 56 and over	29 23	36 29	43 35	50 40	58 46	52	58	63	69	75	81	86	92	98
7/16	Less than 66 66 and over	29 23	36 29	43 35	50 40	58 46	65 52	58	63	69	75	81	86	92	98
1/2	Less than 75 75 and over	29 23	36 29	43 35	50 40	58 46	65 52	72 58	79 63	69	75	81	86	92	98
9/16	Less than 84 84 and over	29 23	36 29	43 35	50 40	58 46	65 52	72 58	79 63	86 69	75	81	86	92	98
5/8	Less than 94 94 and over	29 23	36 29	43 35	50 40	58 46	65 52	72 58	79 63	86 69	93 75	81	86	92	98
		Maximum Allowable Variation, in													
		1/4	5/16	3/8	7/16	1/2	9/16	5/8	11/16	3/4	13/16	7/8	15/16	1	1-1/16

Note: For actual dimensions not shown, use the next higher figure.

DIMENSIONS IN INCHES

Intermediate Stiffeners on One Side Only of Web, Fascia Girders

Thickness of Web, in	Depth of Web, in	Least Panel Dimension, in													
5/16	Less than 31 31 and over	30 20	38 25	30	35	40	45	50	55	60	65	70	75	80	85
3/8	Less than 38 38 and over	30 20	38 25	30	35	40	45	50	55	60	65	70	75	80	85
7/16	Less than 44 44 and over	30 20	38 25	45 30	35	40	45	50	55	60	65	70	75	80	85
1/2	Less than 50 50 and over	30 20	38 25	45 30	53 35	40	45	50	55	60	65	70	75	80	85
9/16	Less than 56 56 and over	30 20	38 25	45 30	53 35	60 40	45	50	55	60	65	70	75	80	85
5/8	Less than 63 63 and over	30 20	38 25	45 30	53 35	60 40	68 45	50	55	60	65	70	75	80	85
		Maximum Allowable Variation, in													
		1/4	5/16	3/8	7/16	1/2	9/16	5/8	11/16	3/4	13/16	7/8	15/16	1	1-1/16

Note: For actual dimensions not shown, use the next higher figure.

Intermediate Stiffeners on Both Sides of Web, Fascia Girders

Thickness of Web, in	Depth of Web, in	Least Panel Dimension, in													
5/16	Less than 47 47 and over	33 26	41 33	49 39	46	53	59	66	72	79	85	92	98	105	112
3/8	Less than 56 56 and over	33 26	41 33	49 39	57 46	53	59	66	72	79	85	92	98	105	112
7/16	Less than 66 66 and over	33 26	41 33	49 39	57 46	65 53	73 59	66	72	79	85	92	98	105	112
1/2	Less than 75 75 and over	33 26	41 33	49 39	57 46	65 53	73 59	81 66	72	79	85	92	98	105	112
9/16	Less than 84 84 and over	33 26	41 33	49 39	57 46	65 53	73 59	81 66	89 72	79	85	92	98	105	112
5/8	Less than 94 94 and over	33 26	41 33	49 39	57 46	65 53	73 59	81 66	89 72	98 79	85	92	98	105	112
		Maximum Allowable Variation, in													
		1/4	5/16	3/8	7/16	1/2	9/16	5/8	11/16	3/4	13/16	7/8	15/16	1	1-1/16

Note: For actual dimensions not shown, use the next higher figure.

No Intermediate Stiffeners, Interior or Fascia Girders

Thickness of Web, in	Depth of Web, in																
Any	38	47	56	66	75	84	94	103	113	122	131	141	150	159	169	178	188
	Maximum Allowable Variation, in																
	1/4	5/16	3/8	7/16	1/2	9/16	5/8	11/16	3/4	13/16	7/8	15/16	1	1-1/16	1-1/8	1-3/16	1-1/4

Annex D (Normative)
Manufacturer's Stud Base Qualification Requirements

This annex is part of this standard and includes mandatory elements for use with this standard.

D1. Purpose

The purpose of these requirements is to prescribe tests for the stud manufacturer's certification of a stud base for welding under shop or field conditions.

D2. Responsibility for Tests

The stud manufacturer shall be responsible for the performance of the qualification test. These tests may be performed by a testing agency satisfactory to the Engineer. The agency performing the tests shall submit a certified report to the manufacturer of the studs giving procedures and results for all tests including the information described under D10.

D3. Extent of Qualification

Qualification of a stud base shall constitute qualification of stud bases with the same geometry, flux, and arc shield, having the same diameter and diameters that are smaller by less than 3 mm [1/8 in]. For example, qualification of a 19 mm [3/4 in] shank diameter stud base shall not constitute qualification for a 16 mm [5/8 in] shank diameter stud, but would constitute qualification for a stud base having a shank diameter of 17 mm [5/8 in]. A stud base qualified with an approved grade of ASTM A 108 steel shall constitute qualification for all other approved grades of A 108 steel (see 9.3.1) provided that all other provisions described herein are complied with.

D4. Duration of Qualification

A size of stud base with arc shield, once qualified, shall be considered qualified until the stud manufacturer makes any change in the stud-base geometry, material, flux, or arc shield that affects the welding characteristics.

D5. Preparation of Specimens

D5.1 Test specimens shall be prepared by welding representative studs to suitable specimen plates of Grade 250 [36] steel or any of the other materials described in 1.2.2. When studs are to be welded through decking, the studbase qualification test shall include decking representative of that to be used in construction. Welding shall be done in the flat position (plate surface horizontal). Tests for threaded studs shall be on blanks (studs without threads).

D5.2 Studs shall be welded with power source, welding gun, and automatically controlled equipment as recommended by the stud manufacturer. Welding voltage, current, and time (see D6) shall be measured and recorded for each specimen. Lift and plunge shall be at the optimum setting as recommended by the manufacturer.

D6. Number of Test Specimens

D6.1 For studs 22 mm [7/8 in] or less in diameter, thirty test specimens shall be welded consecutively with constant optimum time, but with current 10% above optimum. For studs over 22 mm [7/8 in] diameter, 10 test specimens shall be welded consecutively with constant optimum time, but current and time shall be the midpoint of the range normally recommended by the manufacturer for production welding.

D6.2 For studs 22 mm [7/8 in] or less in diameter, 30 test specimens shall be welded consecutively with constant optimum time, but with current 10% below optimum. For studs over 22 mm [7/8 in] diameter, 10 test specimens shall be welded consecutively with constant optimum time, but with current 5% below optimum.

D7. Tests

D7.1 Tension Tests. Ten of the specimens welded in conformance with D6.1 and ten in conformance with D6.2 shall be subjected to a tension test in a fixture similar to that shown in Figure 9.2, except that studs without heads may be gripped on the unwelded end in the jaws of the tension testing machine. A stud base shall be considered as qualified if all test specimens have a tensile strength equal to or above the minimum described in 9.3.1.

D7.2 Bend Test Studs 22 mm or Less in Diameter. Twenty of the specimens welded in conformance with D6.1 and twenty in conformance with D6.2 shall be bend tested by being bent alternately 30° from their original axis in opposite directions until failure occurs. Studs shall be bent in a bend testing device as shown in Figure D.1A, except that studs less than 12 mm [1/2 in] diameter, may be bent using a device as shown in Figure D.1B. A stud base shall be considered as qualified if, on all test specimens, fracture occurs in the plate material or shank of the stud and not in the weld or HAZ. All test specimens for studs over 22 mm [7/8 in] will be tested only for tensile strength, Figure 9.2.

D8. Retests

If failure occurs in a weld or the HAZ in any of the bend test groups of D7.2 or at less than specified minimum tensile strength of the stud in any of the tension groups in D7.1, a new test group (described in D6.1 or D6.2, as applicable) shall be prepared and tested. If such failures are repeated, the stud base shall fail to qualify.

D9. Acceptance

For a manufacturer's stud base and arc shield combination to be qualified, each stud of each group of 30 studs shall, by test or retest, meet the requirements described in D7. Qualification of a given diameter of stud base shall be considered qualification for stud bases of the same nominal diameter (see D3, stud-base geometry, material, flux, and arc shield).

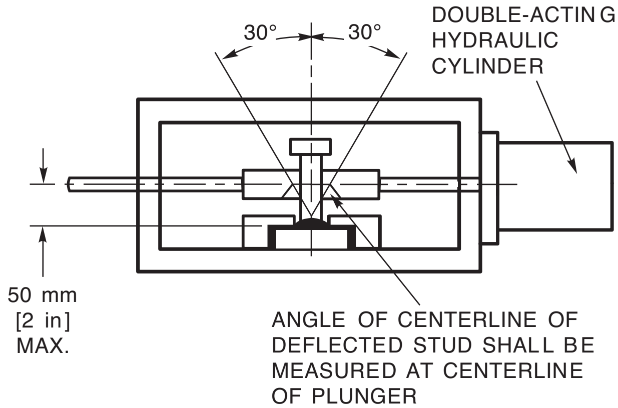
D10. Manufacturer's Qualification Test Data

The test data shall include the following:

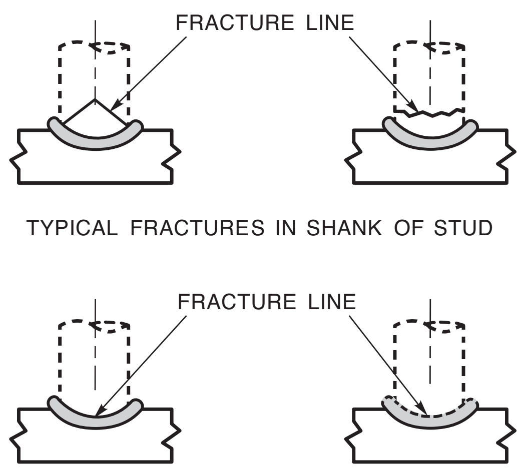
(1) Drawings showing shapes and dimensions with tolerances of stud, arc shields, and flux

(2) A complete description of materials used in the studs, including the quantity and type of flux, and a description of the arc shields

(3) Certified results of required laboratory tests



Notes:
1. Fixture holds specimen and stud shall be bent 30° alternately in opposite directions.
2. Load may be applied with hydraulic cylinder (shown) or fixture adapted for use with tension test machine.



Note: Fracture in weld near stud fillet remains on plate.

Note: Fracture through flash torn from plate.

TYPICAL WELD FAILURES

Figure D.1A—Bend Testing Device (see D7.2)

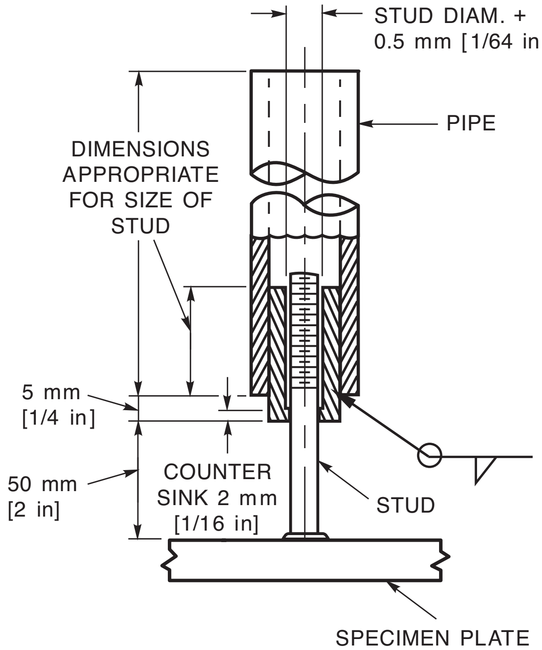


Figure D.1B—Suggested Type of Device for Qualification Testing of Small Studs (see D7.2)

Annex E (Normative)

This annex is part of this standard and includes mandatory elements for use with this standard.

Part A
Qualification and Calibration of the UT Unit with Other Approved Reference Blocks (see Figure 8.5B)

E1. Longitudinal Mode

E1.1 Distance Calibration

E1.1.1 The transducer shall be set in position

H on the DC block, or
M on the DSC block

E1.1.2 The instrument shall be adjusted to produce indications at 25 mm [1 in], 50 mm [2 in], 75 mm [3 in], 100 mm [4 in], etc., on the display.

NOTE: This procedure establishes a 250 mm [10 in] screen calibration and may be modified to establish other distances as allowed by 8.18.4.1.

E1.2 Amplitude. With the transducer in position described in E1.1, the gain shall be adjusted until the maximized indication from the first back reflection attains 50% to 75% screen height.

E2. Shear Wave Mode (Transverse)

E2.1 Sound Entry (Index) Point Check

E2.1.1 The search unit shall be set in position J or L on the DSC block; or I on the DC block.

E2.1.2 The search unit shall be moved until the signal from the radius is maximized.

E2.1.3 The point on the search unit that is in line with the line on the calibration block shall be indicative of the point of sound entry.

NOTE: Use this sound entry point for all further distance and angle checks.

E2.2 Sound Path Angle Check

E2.2.1 The transducer shall be set in position:

K on the DSC block for 45° through 70°
N on the SC block for 70°

O on the SC block for 45°
P on the SC block for 60°

E2.2.2 The transducer shall be moved back and forth over the line indicative of the transducer angle until the signal from the radius is maximized.

E2.2.3 The sound entry point on the transducer shall be compared with the angle mark on the calibration block (tolerance ±2°).

E2.3 Distance Calibration

E2.3.1 The transducer shall be set in position L on the DSC block. The instrument shall be adjusted to attain indications at 75 mm [3 in] and 180 mm [7 in] on the display.

E2.3.2 The transducer shall be set in position J on the DSC block (any angle). The instrument shall be adjusted to attain indications at 25 mm [1 in], 125 mm [5 in], and 230 mm [9 in] on the display.

E2.3.3 The transducer shall be set in position I on the DC block (any angle). The instrument shall be adjusted to attain indication at 25 mm [1 in], 50 mm [2 in], 75 mm [3 in], 100 mm [4 in], etc., on the display.

NOTE: This procedure establishes a 250 mm [10 in] screen calibration and may be modified to establish other distances as allowed by 8.18.5.1.

E2.4 Amplitude or Sensitivity Calibration

E2.4.1 The transducer shall be set in position L on the DSC block (any angle). The maximized signal from the 0.8 mm [1/32 in] slot shall be adjusted to attain a horizontal reference-line height indication.

E2.4.2 The transducer shall be set on the SC block in position:

N for 70° angle
O for 45° angle
P for 60° angle

The maximized signal from the 1.6 mm [1/16 in] hole shall be adjusted to attain a horizontal reference-line height indication.

E2.4.3 The decibel reading obtained in E2.4.1 or E2.4.2 shall be used as the "Reference level, 'b,' " on the Test Report Sheet (Annex E, Part B, Form E-4) in conformance with 8.16.1.

E3. Horizontal Linearity Procedure

NOTE: As this qualification procedure is performed with a straight beam search unit that produces longitudinal waves with a sound velocity of almost double that of shear waves, it shall be necessary to double the shear wave distance ranges to be used in applying this procedure.

E3.1 A straight beam search unit meeting the requirements of 8.15.6 shall be coupled in position:

G on the IIW block (Figure 8.6)
T or U on the DS block (Figure 8.6)

E3.2 A minimum of 5 back reflections shall be attained in the qualification range being certified.

E3.3 The first and fifth back reflections shall be adjusted to their proper locations with use of the distance calibration and zero delay adjustments.

E3.4 Each indication shall be adjusted to reference level with the gain or attenuation control for horizontal location examination.

E3.5 Each intermediate trace deflection location shall be correct within ±2% of the screen width.

Part B
UT Equipment Qualification Procedures

This annex contains examples for use of three forms, E-1, E-2, and E-3, recording of UT data. Each example of forms E-1, E-2, and E-3 shows how the forms may be used during the UT of welds. Form E-4 is for reporting results of UT of welds.

UT Unit Certification

Ultrasonic unit
Model UT77 Serial no. 00006

Date 05-05-2015

By I. C. BLIPS

Search unit
Size 25 mm [1 in] Type BT
Frequency 2.25 MHz

ASNT Level II

TABULATION CHART					
No.	a dB Reading	b % Scale	c Corrected Reading	d dB Error	e Collective dB Error
1	6	69	7.1	–1.1	–2.3
2	12	75	12.4	–0.4	–1.2
3	18	75	18.3	–0.3	–0.8
4	24	77	24.1	–0.1	–0.5
5	30	77	30.1	–0.1	–0.4
6	36	77	36.1	–0.1	–0.3
7	42	77	42.1	–0.1	–0.2
8	48	78	48.0	–0.0	–0.1
9	54	77	54.1	–0.1	–0.1
10 (Average 78%—)	60	78	60.0	0.0	0.0
11	66	79	65.9	+0.1	+0.1
12	72	80	71.8	+0.2	+0.3
13	78	81	77.7	+0.3	+0.6
14	84	86	83.1	+0.9	+1.5
15					
16					
17					
18					
19					
20					
21					
22					
23					
24					
25					
26					

Find the average % screen values from column b disregarding the first three and last three tabulations. Use this percentage as $\%_2$ in calculating the Corrected Reading c.

The dB Error d shall be established by subtracting the Corrected Reading from the dB Reading a. Beginning with the tabulated dB Error d nearest to 0.0, collectively add the dB Error d values up and down placing the subtotals in column e (Collective dB Errors).

Moving vertically up and down from the Average % line, find the largest vertical span in which the top and bottom Collective dB Error figures remain at or below 2 dB. Count the number of vertical spaces of movement, subtract one, and multiply the remainder by six. This dB value shall be the acceptable range of the unit.

In order to establish the acceptable range graphically, Form E-2 should be used in conjunction with Form E-1 as follows:

(1) Apply the collective dB Error "e" values vertically on the horizontal offset coinciding with the dB reading values "a."

(2) Establish a curve line passing through this series of points.

(3) Apply a 2 dB high horizontal window over this curve positioned vertically so that the longest section shall be completely encompassed within the 2 dB Error height.

(4) This window length represents the acceptable dB range of the unit.

$$dB_2 = 20 \times \log(\%_2 \div \%_1) + dB_1$$

$\%_2$ (Average) 78 %

Total qualified range 12 dB to 78 dB = 66 dB Total error 1.8 dB

FORM E-1 Total qualified range 11 dB to 80 dB = 69 dB Total error 2.0 dB

Figure E.1—Example of the Use of Form E-1 UT Unit Certification

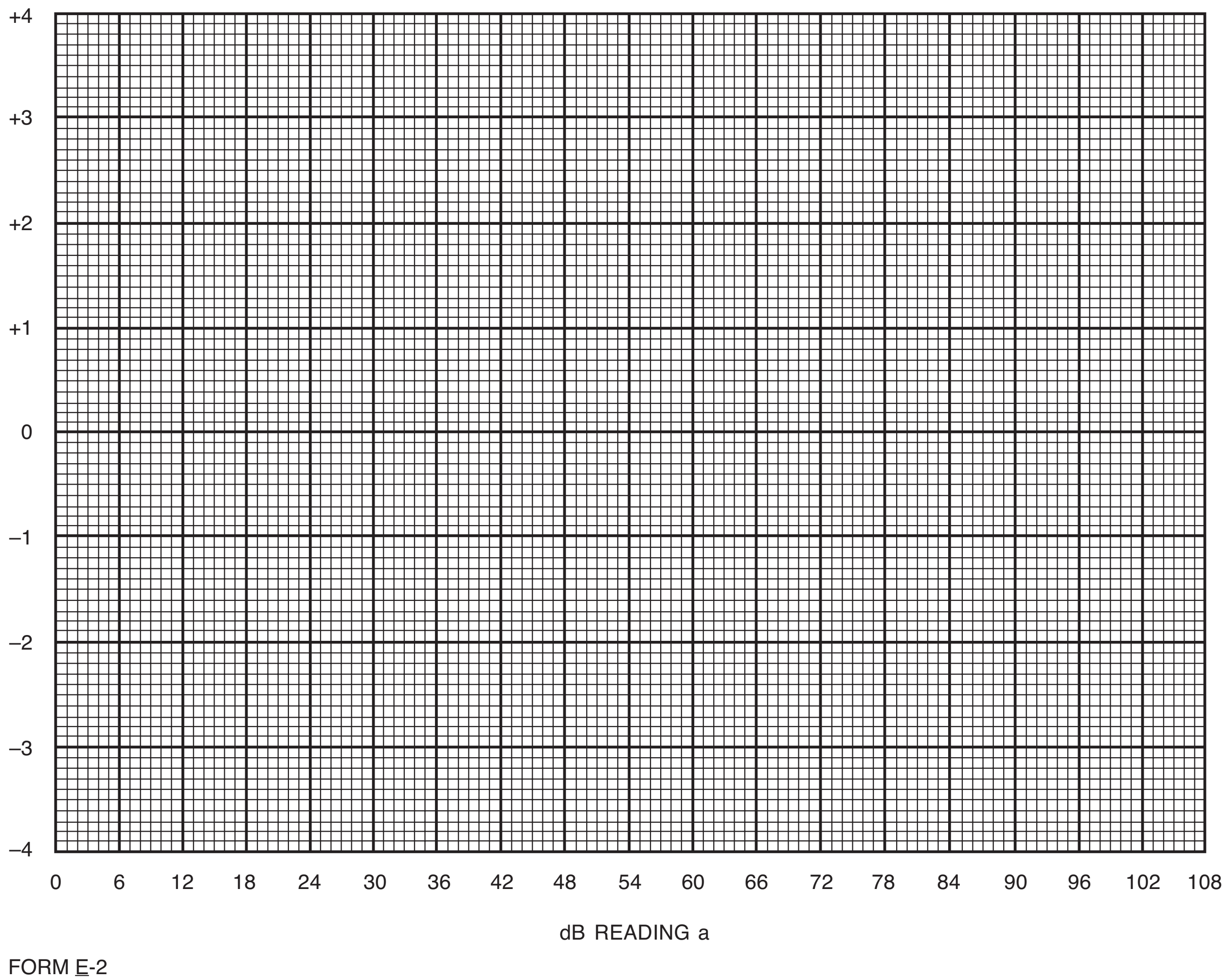
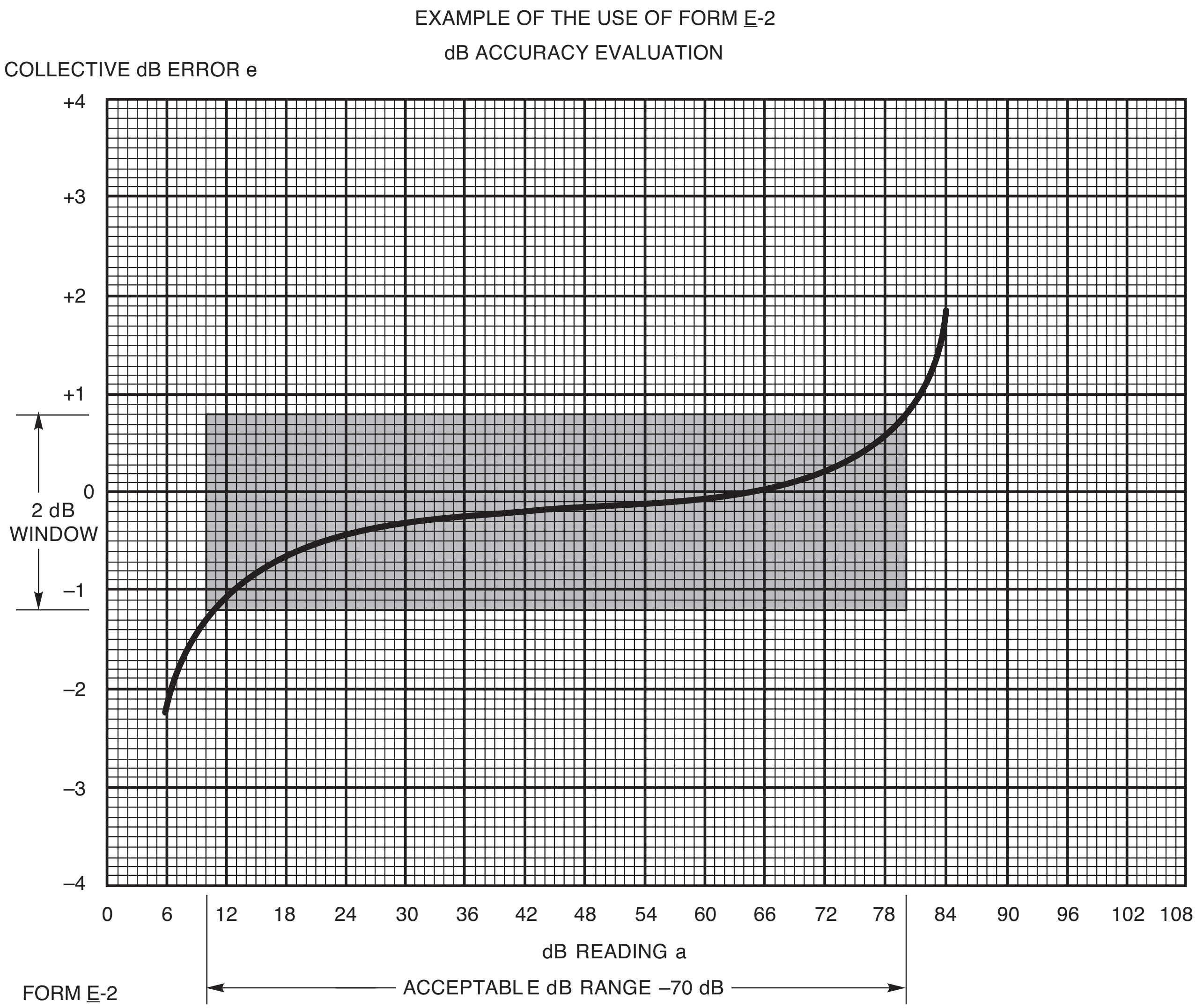


Figure E.2—Example of Form E-2



THE CURVE ON FORM E-2 EXAMPLE IS DERIVED FROM CALCULATIONS FROM FORM E-2 (FIGURE E.2).
THE CROSS HATCHED ON FIGURE E-2 SHOWS THE AREA OVER WHICH THE EXAMPLE UNIT QUALIFIES TO THIS CODE.

Note: The first line of example of the use of Form E-1 is shown in this example.

Figure E.3—Example of the Use of Form E-2

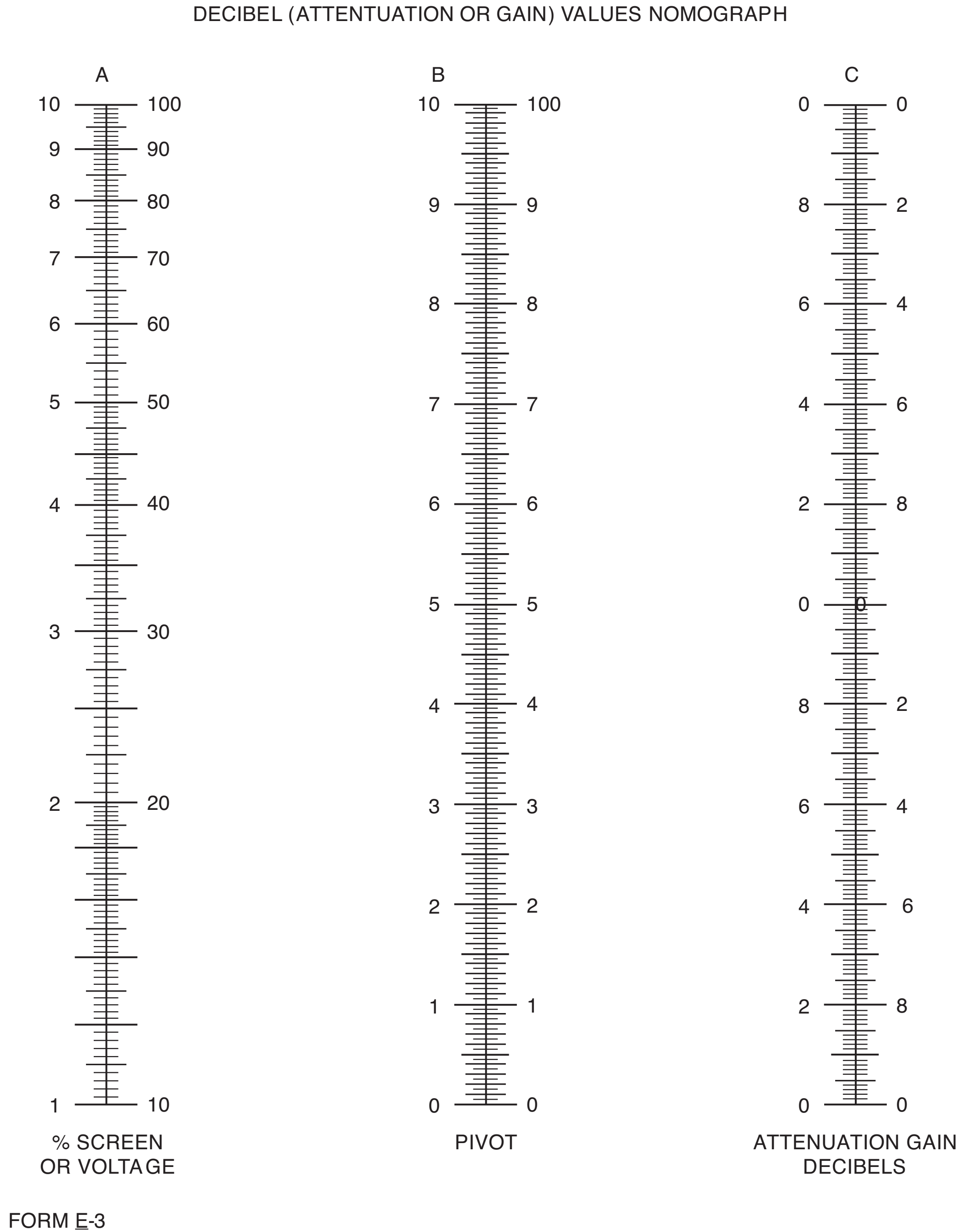
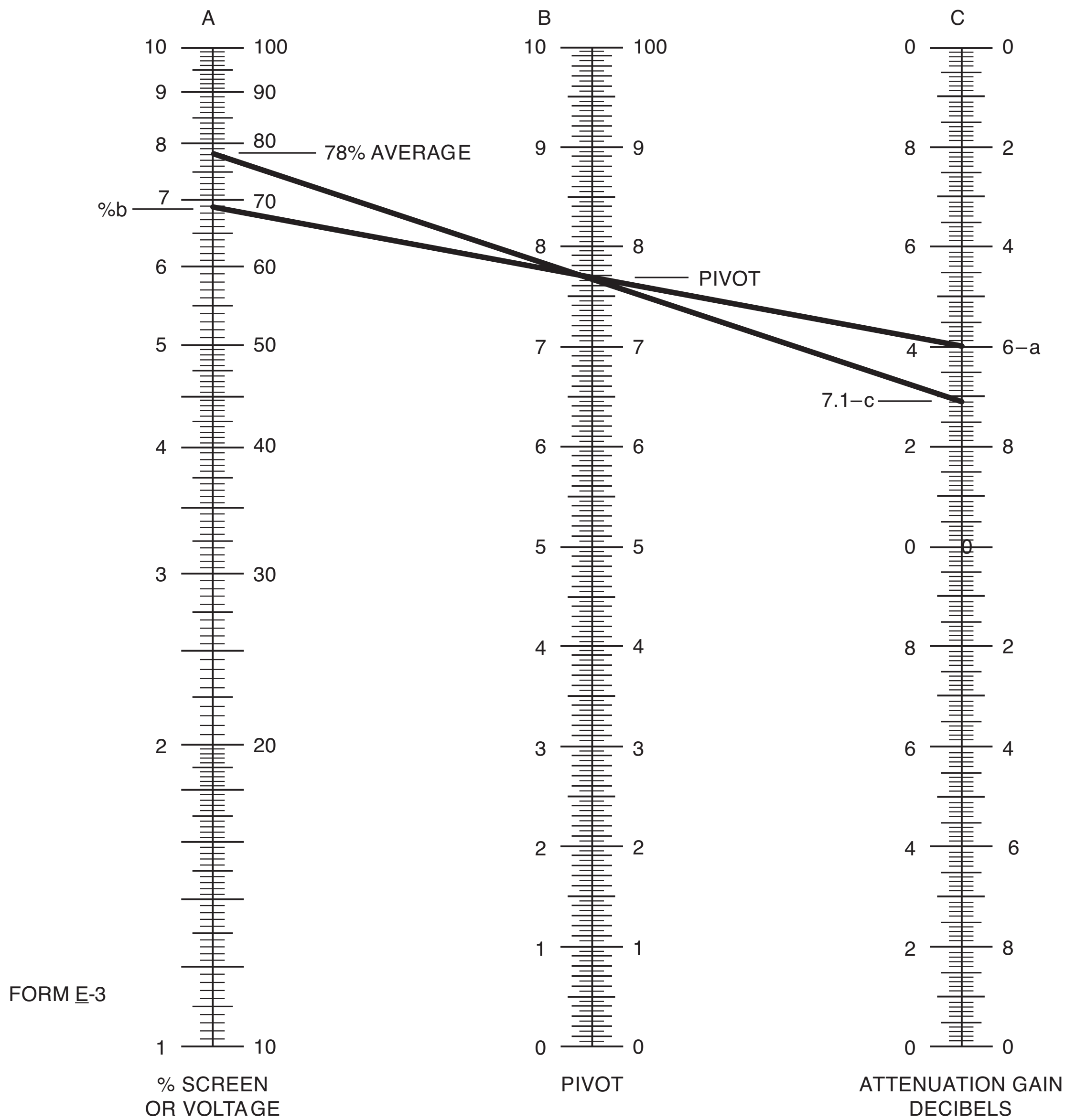


Figure E.4—Example of Form E-3

Notes:
1. The 6 dB reading and 69% scale are derived from the instrument reading and become dB “b_1” and $\%_1$ “c” respectively.
2. $\%_2$ is 78 – constant.
3. dB_2 (which is corrected dB “d”) is equal to 20 times × log (78/69) + 6 or 7.1.

THE USE OF THE NOMOGRAPH IN RESOLVING LINE 3 IS AS SHOWN ON THE FOLLOWING EXAMPLE.

DECIBEL (ATTENTUATION OR GAIN) VALUES NOMOGRAPH



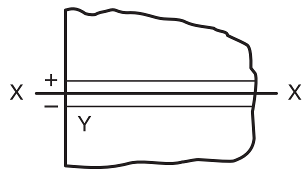
THE CURVE ON FORM E-2 EXAMPLE IS DERIVED FROM CALCULATIONS FROM FORM E-1 EXAMPLE. THE CROSS HATCHED AREA ON FORM E-2 EXAMPLE SHOWS THE AREA OVER WHICH THE EXAMPLE UNIT QUALIFIES TO THIS CODE.

Notes: Procedure for using the Nomograph:
1. Extend a straight line between the decibel reading from Column A applied to the C scale and the corresponding percentage from Column B applied to the A scale.
2. Use the point where the straight line from Step 1 crosses the pivot line B as a pivot line for a second straight line.
3. Extend a second straight line from the average sign point on the A scale, through the pivot point developed in Step 2, and onto the dB scale C.
4. This point on the C scale is indicative of the corrected dB for use in Column C.

Figure E.5—Example of the Use of Form E-3

REPORT OF UT WELDS

Project ______________________________ Report no. ______________



Weld identification ______________________________

Material thickness ______________________________

Weld joint AWS ______________________________

Welding process ______________________________

Quality requirements—section no. ______________________________

Remarks ______________________________

Line number	Indication number	Transducer angle	From Face	Leg[a]	Decibels				Discontinuity					Discontinuity evaluation	Remarks
					Indication level	Reference level	Attenuation factor	Indication rating	Length	Angular distance (sound path)	Depth from “A” surface	Distance			
					a	b	c	d				From X	From Y		
1															
2															
3															
4															
5															
6															
7															
8															
9															
10															
11															
12															
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15															
16															
17															
18															
19															
20															
21															
22															
23															
24															
25															
26															

We, the undersigned, certify that the statements in this record are correct and that the welds were prepared and tested in conformance with the requirements of Clause 8, Part G of AASHTO/AWS D1.5M/D1.5, (__________) *Bridge Welding Code*.
(year)

Test Date ______________________________ Manufacturer or Contractor ______________________________

Inspected By ______________________________ Authorized By ______________________________

[a] Use Leg I, II, or III. See glossary of terms (Clause 3). Date ______________________________

Notes:

1. In order to attain Rating “d”
   a. With instruments with gain control, use the formula a – b – c = d.
   b. With instruments with attenuation control, use the formula b – a – c = d.
   c. A plus or minus sign shall accompany the “d” figure unless “d” is equal to zero.
2. Distance from X is used in describing the location of a weld discontinuity in a direction perpendicular to the weld reference line. Unless this figure is zero, a plus or minus sign shall accompany it.
3. Distance from Y is used in describing the location of a weld discontinuity in a direction parallel to the weld reference line. This figure is attained by measuring the distance from the “Y” end of the weld to the beginning of said discontinuity.
4. Evaluation of Retested Repaired Weld Areas shall be tabulated on a new line on the report form. If the original report form is used, R_n shall prefix the indication number. If additional forms are used, the R number shall prefix the report number.

Figure E.6—Form E-4—Report of UT of Welds

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Annex F (Normative) Guidelines on Alternative Methods for Determining Preheat

This annex is part of this standard and includes mandatory elements for use with this standard.

F1. Introduction

The purpose of this guide is to provide some optional alternative methods for determining welding conditions (principally preheat) to avoid cold cracking. The methods are based primarily on research on small scale tests carried out over many years in several laboratories worldwide. No method is available for predicting optimum conditions in all cases, but the guide does consider several important factors such as hydrogen level and steel composition not explicitly included in the requirements of Table 6.3. The guide may therefore be of value in indicating whether the requirements of Table 6.3 are overly conservative or in some cases not sufficiently demanding.

The user is referred to the Commentary, AWS D1.1, *Structural Welding Code—Steel*, for more detailed presentation of the background scientific and research information leading to the two methods proposed.

In using this guide as an alternative to Table 6.3, careful consideration shall be given to the assumptions made, the values selected, and past experience.

F2. Methods

Two methods are used as the basis for estimating welding conditions to avoid cold cracking:

(1) HAZ hardness control

(2) Hydrogen control

F3. HAZ Hardness Control

F3.1

The provisions included in this guide for use of this method shall be restricted to fillet welds.

F3.2

This method is based on the assumption that cracking will not occur if the hardness of the HAZ is kept below some critical value. This is achieved by controlling the cooling rate below a critical value dependent on the hardenability of the steel. Hardenability of steel in welding relates to its propensity towards formation of a hard HAZ and can be characterized by the cooling rate necessary to produce a given level of hardness. Steels with high hardenability can, therefore, produce a hard HAZ at slower cooling rates than a steel with lower hardenability. Equations and graphs are available in the technical literature that relate the weld cooling rate to the thickness of the steel members, type of joint, welding conditions, and variables.

F3.3

The selection of the critical hardness will depend on a number of factors such as steel type, hydrogen level, restraint, and service conditions. Laboratory tests with fillet welds show that HAZ cracking does not occur if the HAZ Vickers Hardness No. (HV) is less than 350 HV even with high-hydrogen electrodes. With low-hydrogen electrodes, hardnesses of 400 HV may be tolerated without cracking. Such hardnesses, however, may not be tolerable in service where there is an increased risk of stress corrosion cracking, brittle fracture initiation, or other risks for the safety or serviceability of the structure.

The critical cooling rate for a given hardness may be approximately related to the carbon equivalent of the steel (see Figure F.2). Since the relationship is only approximate, the curve shown in Figure F.2 may be conservative for plain carbon and plain-carbon-manganese steels and thus allow the use of the high hardness curve with less risk. Some low-alloy steels, particularly those containing columbium (niobium), may be more hardenable than Figure F.2 indicates, and the use of the lower hardness curve is recommended.

F3.4

Although the method may be used to determine a preheat level, its main value is in determining the minimum heat input (and hence minimum weld size) that prevents excessive hardening. It is particularly useful for determining the minimum size of single-pass fillet welds that can be deposited without preheat.

F3.5

The hardness approach does not consider the possibility of weld metal cracking, but from experience it has been found that the heat input determined by this method is usually adequate to prevent weld metal cracking in most cases in fillet welds if the electrode is not a high-strength filler metal; generally, it should be a low-hydrogen type (e.g., low-hydrogen [SMAW] electrode, GMAW, FCAW, SAW).

F3.6

Because the method depends solely on controlling the HAZ hardness, the hydrogen level and restraint are not explicitly considered.

F3.7

This method shall not be applicable to quenched and tempered steels (see F5.2.3 for limitations).

F4. Hydrogen Control

F4.1

The hydrogen control method is based on the assumption that cracking will not occur if the average quantity of hydrogen remaining in the joint after it has cooled down to about 50°C [120°F] does not exceed a critical value dependent on the composition of the steel and the restraint. The preheat necessary to allow excessive hydrogen to diffuse out of the joint can be estimated using this method.

F4.2

This method is based mainly on results of restrained PJP groove weld tests; the weld metal used in the tests matched the parent metal.

There has not been extensive testing of this method on fillet welds; however, by allowing for restraint, the method has been suitably adapted for those welds.

F4.3

A determination of the restraint level and the original hydrogen level in the weld pool shall be required for the hydrogen method. In this guide, restraint shall be classified as high, medium, and low, and the category shall be established from experience.

F4.4

The hydrogen control method is based on a single low heat input weld bead representing a root pass and assumes that the HAZ hardens. The method shall be, therefore, particularly useful for high-strength, low-alloy steels having quite high hardenability where hardness control is not always feasible. Consequently, because it assumes that the HAZ fully hardens, the predicted preheat may be too conservative for carbon steels.

F5. Selection of Method

The following procedure, for selection of the more appropriate method of F3 or F4, is recommended as a guide.

F5.1

Both the carbon content and carbon equivalent of the steel should be determined:

$$CE = C + \frac{(Mn + Si)}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15}$$

to locate the zone classification of the steel in Figure F.1 (see F6.1.1 for different ways to obtain the chemical analysis).

F5.2

The performance characteristics of each zone and the recommended action are as follows:

F5.2.1 Zone I. Cracking is unlikely but may occur with high hydrogen or high restraint. The hydrogen control method should be used to determine preheat for steels in this zone.

F5.2.2 Zone II. The hardness control method should be used and HV350 or HV400 hardness number should be selected to determine the minimum energy input for single-pass fillet welds without preheat. If that energy input is not practical, the hydrogen method should be used to determine preheat.

(1) For groove welds, the hydrogen control method should be used to determine preheat.

(2) For steels with high carbon, a minimum energy to control hardness and a minimum preheat to control hydrogen both may be required, for fillet welds and for groove welds.

F5.2.3 Zone III. The hydrogen control method should be used. Where heat input is restricted to preserve the HAZ properties (e.g., some quenched and tempered steels), the hydrogen control method should be used to determine preheat.

F6. Detailed Computation Guide

F6.1 Hardness Method

F6.1.1 Calculate the carbon equivalent as follows:

$$CE = C + \frac{(Mn + Si)}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15}$$

The chemical analysis may be obtained from the following:

(1) Mill test certificates

(2) Typical production chemical analysis (from the mill)

(3) Specification chemical analysis (using maximum values)

(4) User tests (chemical analysis)

F6.1.2 The critical cooling rate shall be determined for a selected maximum HAZ hardness of either 400 HV or 350 HV, from Figure F.2.

F6.1.3 Using applicable thicknesses for "flange" and "web" plates, the appropriate diagram from Figure F.3 shall be selected and the minimum input energy shall be determined for single-pass fillet welds. Keep in mind that this energy input applies to SAW.

F6.1.4 For other processes, the minimum energy input for single-pass fillet welds can be estimated by multiplying the energy estimated in F6.1.3 by the factors below:

Welding Process	Multiplication Factor
SAW	1
SMAW	1.50
GMAW, FCAW	1.25

F6.1.5 Figure F.4 may be used to determine fillet sizes as a function of energy input.

F6.2 Hydrogen Control Method

F6.2.1 The value of the composition parameter, P_{cm}, shall be calculated as follows:

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B$$

The chemical analysis shall be determined as in F6.1.1.

F6.2.2 The hydrogen level shall be determined and defined as follows:

F6.2.2.1 H4 Extra-Low Hydrogen. Consumables thus labeled should have the following:

(1) A diffusible hydrogen content of less than 4 mL/100 g deposited metal when measured using the latest edition of AWS A4.3, *Standard Procedures for Determination of Diffusible Hydrogen Content of Martensitic, Bainitic, and Ferritic Steel Weld Metal Produced by Arc Welding*, or

(2) A moisture content of electrode covering of 0.2% maximum in conformance with AWS A5.1/A5.1M or A5.5/A5.5M.

This may be established by testing each type, brand, or wire/flux combination used after removal from the package or container and exposure for the intended duration, with due consideration of actual storage conditions prior to immediate use. The following may be assumed to meet this requirement:

(a) Low-hydrogen electrodes taken from hermetically sealed containers, dried at between 370 ˚C and 425 ˚C [700 ˚F and 800 ˚F] for one hour and used within two hours after removal

(b) GMAW with clean solid wires

F6.2.2.2 H8 Low-Hydrogen. These consumables shall conform to the following requirements:

(1) A diffusible hydrogen content of less than 8 mL/100 g deposited metal when measured using AWS A4.3 or

(2) A moisture content of electrode covering of 0.4% maximum in conformance with AWS A5.1/A5.1M.

This may be established by a test on each type, brand of consumable, or wire/flux combination used. The following may be assumed to meet this requirement:

(a) Low-hydrogen electrodes taken from hermetically sealed containers conditioned in conformance with 6.5.2 of the code and used within four hours after removal

(b) SAW with dry flux. These consumables are expected to give a diffusible hydrogen content of "less than 16 mL/100 g," which may not meet this 8 mL/100 g definition.

F6.2.2.3 H16 Hydrogen Limit. These other consumables do not meet the requirements of H4 or H8.

F6.2.3 The susceptibility index grouping from Table F.1 should be determined.

F6.2.3.1 Required minimum preheat levels and interpass temperatures are given in Table F.2 for three levels of restraint. The restraint level to be used shall be determined in conformance with F6.2.3.2.

F6.2.3.2 Restraint. The degree of restraint of weld types should be determined on the basis of experience, engineering judgment, research, or calculation. Three levels of restraint have been provided:

(1) *Low Restraint.* This level describes common fillet and groove welded joints in which a reasonable freedom of movement of members exists.

(2) *Medium Restraint.* This level describes fillet and groove welded joints in which, because of members being already attached to structural work, a reduced freedom of movement exists.

(3) *High Restraint.* This level describes welds in which there is almost no freedom of movement for members joined (such as repair welds, especially in thick material).

Table F.1
Susceptibility Index Grouping as Function of Hydrogen Level "H" and Composition Parameter P_{cm} (see F6.2.3)

	Susceptibility Index[b] Grouping[c]				
	Carbon Equivalent = P_{cm}[a]				
Hydrogen Level, H	<0.18	<0.23	<0.28	<0.33	<0.38
H4	A	B	C	D	E
H8	B	C	D	E	F
H16	C	D	E	F	G

[a] $P_{cm} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B$

[b] Susceptibility index = 12 P_{cm} + $\log_{10}$ H.

[c] Susceptibility Index Groupings, A through G, encompass the combined effect of the composition parameter, P_{cm}, and hydrogen level, H, in conformance with the formula shown in Note b.

The exact numerical quantities shall be obtained from the Note b formula using the described values of P_{cm} and the following values of H, given in mL/100 g of weld metal (see F6.2.2, a, b, c):

H4 < 4; H8 < 8; H16 < 16.

For greater convenience, Susceptibility Index Groupings have been expressed in the table by means of letters, A through G, to cover the following narrow ranges:

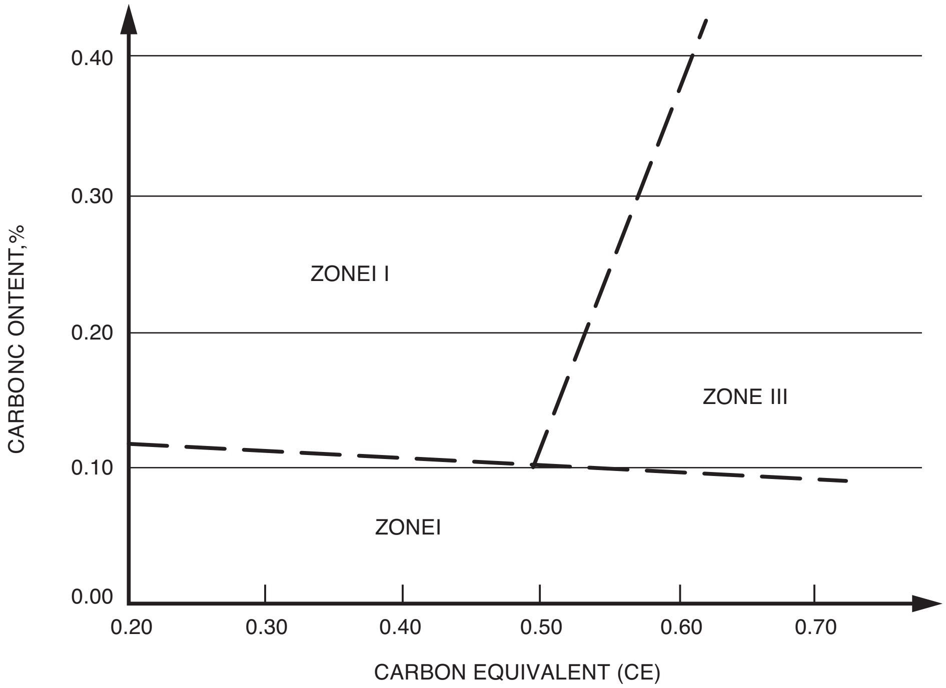
A = 3.0; B = 3.1–3.5; C = 3.6–4.0; D = 4.1–4.5; E = 4.6–5.0; F = 5.1–5.5; G = 5.6–7.0.

These groupings are used in Table F.2 in conjunction with restraint and thickness to determine the minimum preheat and interpass temperature.

Table F.2
Minimum Preheat and Interpass Temperatures for Three Levels of Restraint (see F6.2.3.1)

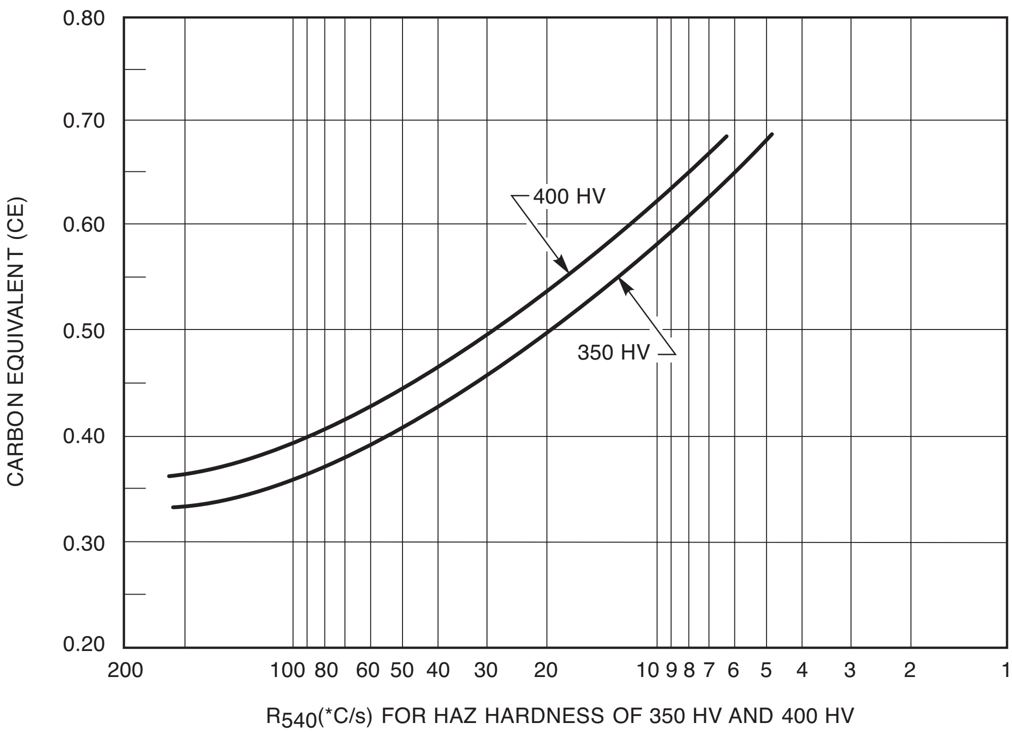
Restraint Level	Thickness[a] mm [in]	Minimum Preheat and Interpass Temperature, °C [°F] — Susceptibility Index Grouping: A	B	C	D	E	F	G
Low	<10 [3/8]	<20 [65]	<20 [65]	<20 [65]	<20 [65]	60 [140]	135 [280]	150 [300]
	10–20 [3/8–3/4]	<20 [65]	<20 [65]	20 [65]	60 [140]	100 [210]	135 [280]	150 [300]
	20–40 [3/4–1-1/2]	<20 [65]	<20 [65]	20 [65]	80 [175]	110 [230]	135 [280]	150 [300]
	40–75 [1-1/2–3]	20 [65]	20 [65]	40 [100]	95 [200]	120 [250]	135 [280]	150 [300]
	>75 [3]	20 [65]	20 [65]	40 [100]	95 [200]	120 [250]	135 [280]	150 [300]
Medium	<10 [3/8]	<20 [65]	<20 [65]	<20 [65]	<20 [65]	70 [160]	135 [280]	160 [320]
	10–20 [3/8–3/4]	<20 [65]	<20 [65]	20 [65]	80 [175]	115 [240]	145 [290]	160 [320]
	20–40 [3/4–1-1/2]	<20 [65]	20 [65]	75 [165]	110 [230]	135 [280]	150 [300]	160 [320]
	40–75 [1-1/2–3]	20 [65]	80 [175]	110 [230]	130 [265]	150 [300]	150 [300]	160 [320]
	>75 [3]	95 [200]	120 [250]	135 [280]	150 [300]	160 [320]	160 [320]	160 [320]
High	<10 [3/8]	<20 [65]	<20 [65]	<20 [65]	40 [100]	110 [230]	150 [300]	160 [320]
	10–20 [3/8–3/4]	<20 [65]	<20 [65]	65 [150]	105 [220]	135 [280]	160 [320]	160 [320]
	20–40 [3/4–1-1/2]	20 [65]	85 [185]	115 [240]	135 [280]	150 [300]	160 [320]	160 [320]
	40–75 [1-1/2–3]	115 [240]	130 [265]	150 [300]	150 [300]	160 [320]	160 [320]	160 [320]
	>75 [3]	115 [265]	130 [265]	150 [300]	150 [300]	160 [320]	160 [320]	160 [320]

[a] Thickness is that of the thicker part welded.



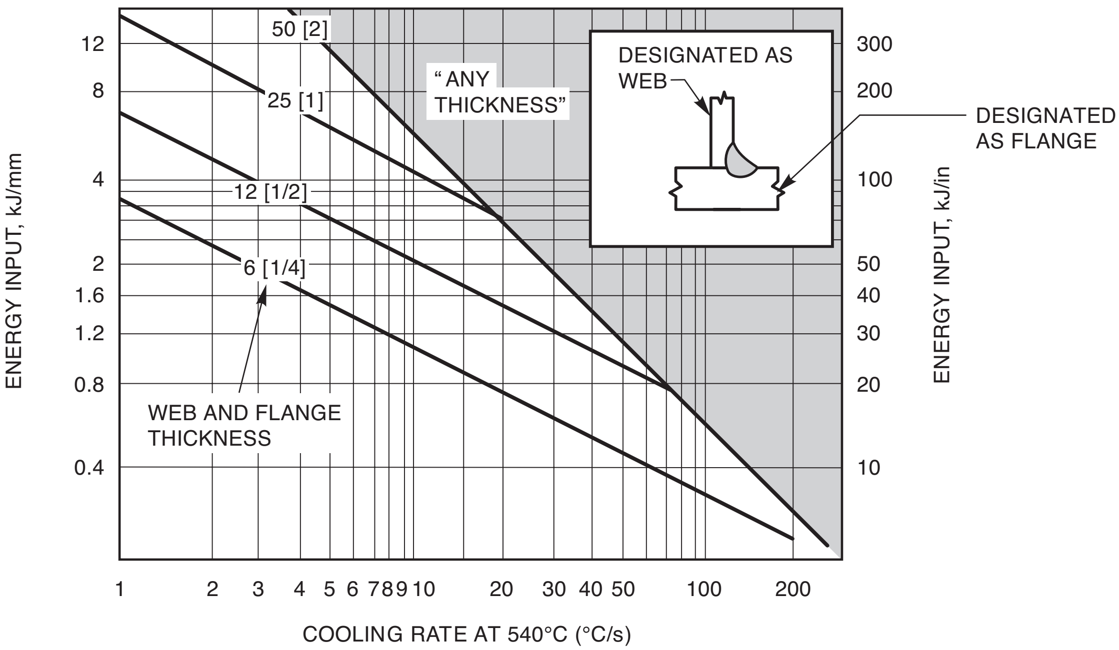
Notes:
1. CE = C + (Mn + Si)/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15.
2. See F5.2.1, F5.2.2, or F5.2.3 for applicable zone characteristics.

Figure F.1—Zone Classification of Steels (see F5.1)



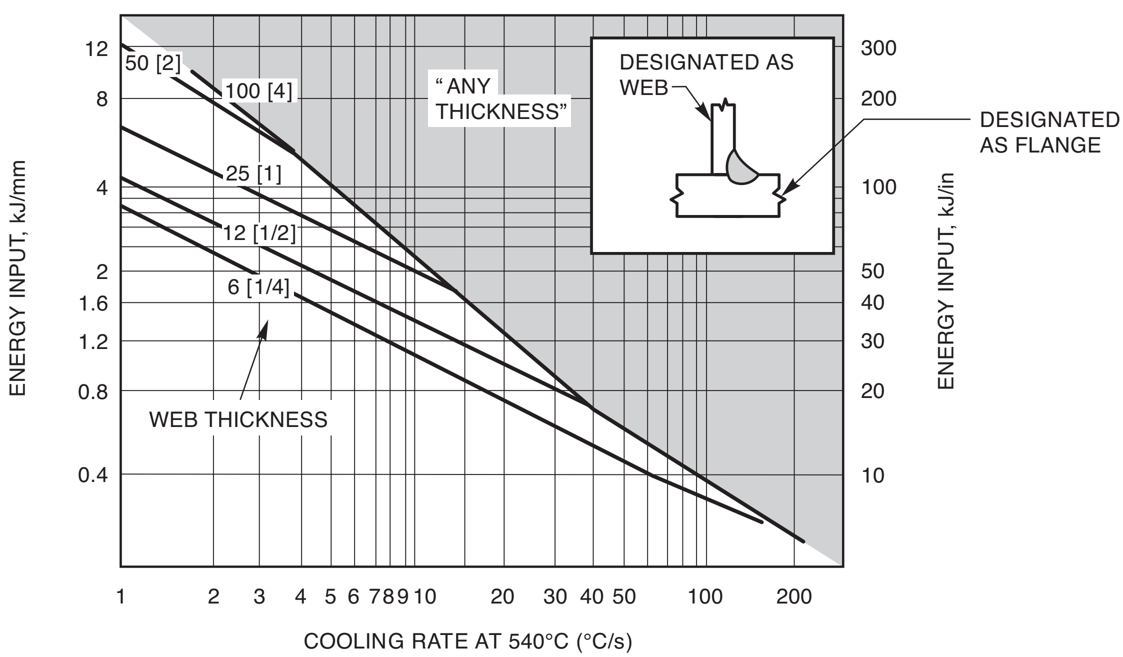
Note: CE = C + (Mn + Si)/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15.

Figure F.2—Critical Cooling Rate for 350 HV and 400 HV (see F6.1.2)



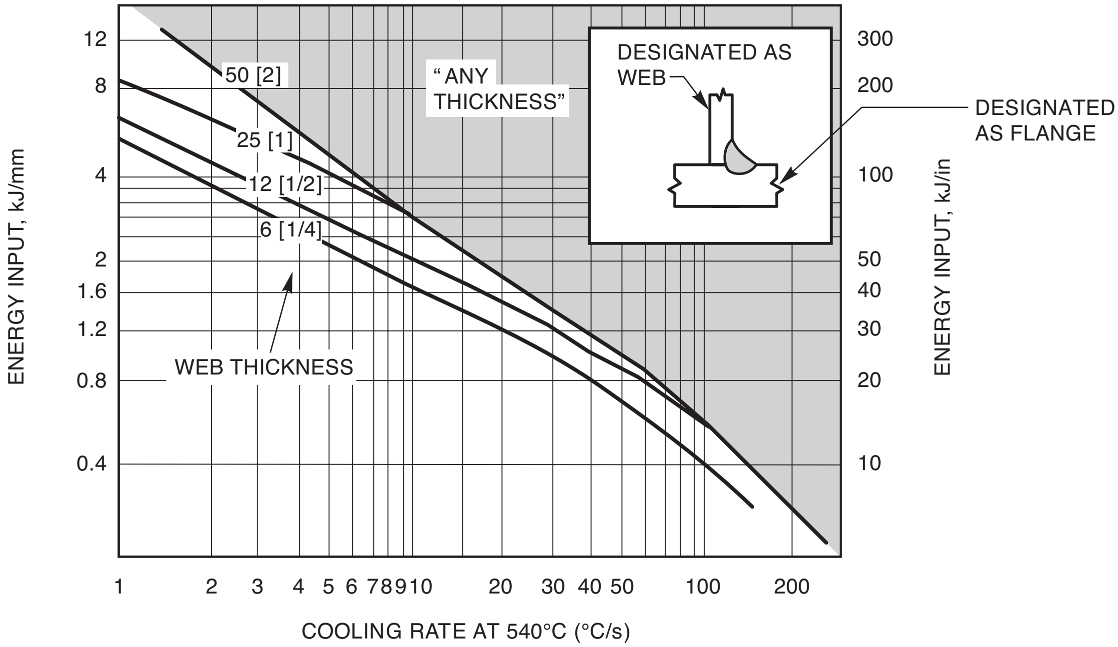
Note: Energy input determined from chart shall not imply suitability for practical applications. For certain combination of thicknesses melting may occur through the thickness.

(A) SINGLE-PASS SAW FILLET WELDS WITH WEB AND FLANGE OF SAME THICKNESS



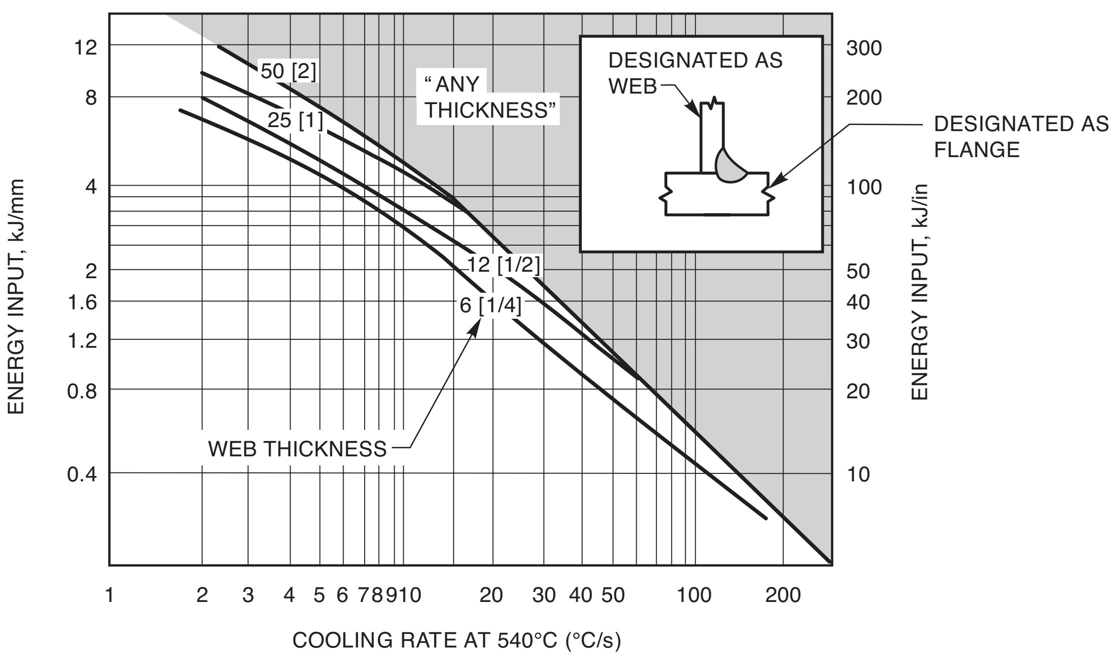
(B) SINGLE-PASS SAW FILLET WELDS WITH 6 mm [1/4 in] FLANGES AND VARYING WEB THICKNESSES

Figure F.3—Charts to Determine Cooling Rates for Single-Pass Submerged Arc Fillet Welds (see F6.1.3)



Note: Energy input determined from chart shall not imply suitability for practical applications. For certain combination of thicknesses melting may occur through the thickness.

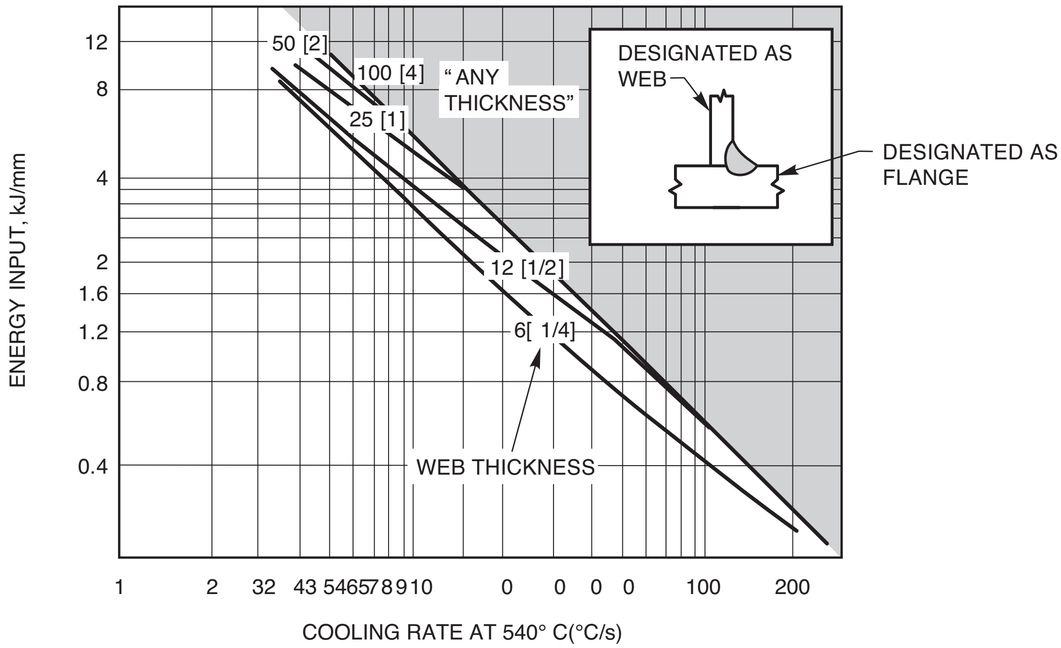
(C) SINGLE-PASS SAW FILLET WELDS WITH 12 mm [1/2 in] FLANGES AND VARYING WEB THICKNESSES



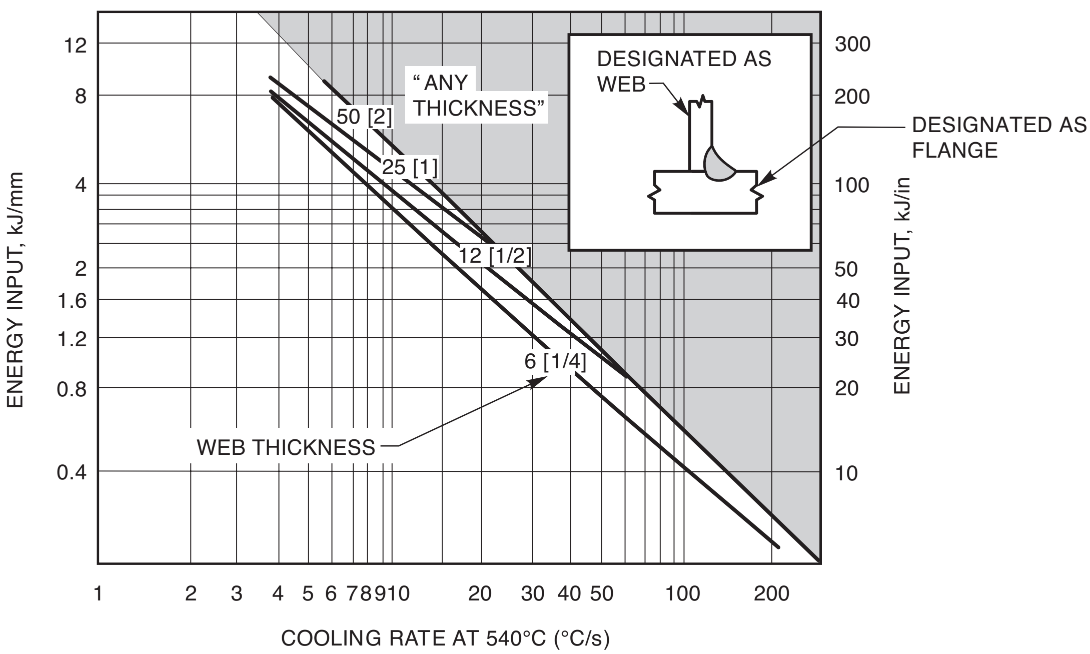
Note: Energy input determined from chart shall not imply suitability for practical applications. For certain combination of thicknesses melting may occur through the thickness.

(D) SINGLE-PASS SAW FILLET WELDS WITH 25 mm [1 in] FLANGES AND VARYING WEB THICKNESSES

Figure F.3 (Continued)—Charts to Determine Cooling Rates for Single-Pass Submerged Arc Fillet Welds (see F6.1.3)



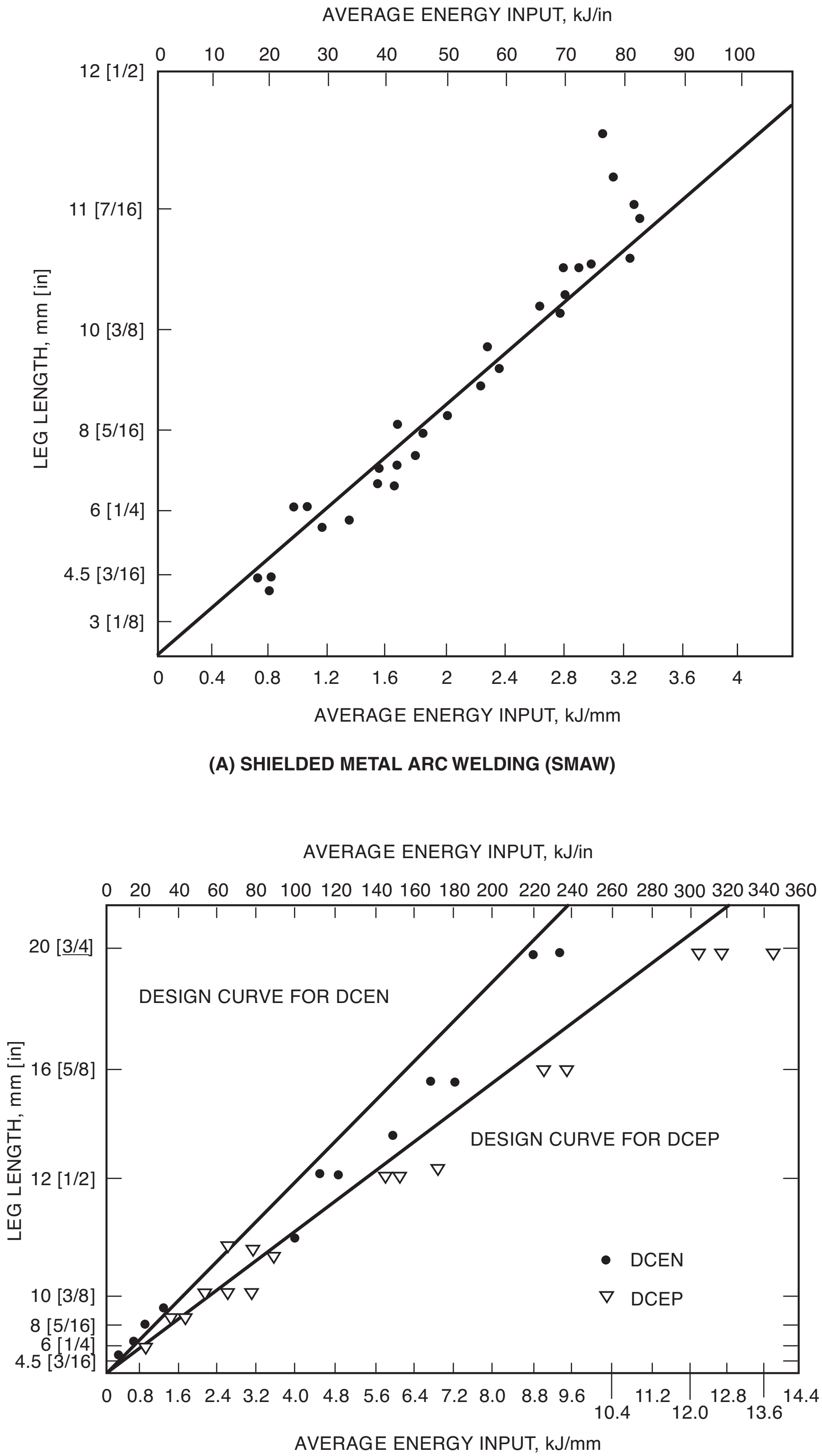
(E) SINGLE-PASS SAW FILLET WELDS WITH 50 mm [2 in] FLANGES AND VARYING WEB THICKNESSES



Note: Energy input determined from chart shall not imply suitability for practical applications. For certain combination of thicknesses melting may occur through the thickness.

(F) SINGLE-PASS SAW FILLET WELDS WITH 100 mm [4 in] FLANGES AND VARYING WEB THICKNESSES

Figure F.3 (Continued)—Charts to Determine Cooling Rates for Single-Pass Submerged Arc Fillet Welds (see F6.1.3)



(A) SHIELDED METAL ARC WELDING (SMAW)

(B) SUBMERGED ARC WELDING (SAW)

Figure F.4—Relation Between Fillet Weld Size and Energy Input (see F6.1.5)

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Annex G (Normative)

Welding Requirements for Conventional, Nonfracture Critical AASHTO M 270M/M 270 (A709/A709M) HPS 485W [HPS 70W] Components with Reduced Preheat and Interpass Temperature

This annex is part of this standard and includes mandatory elements for use with this standard.

G1. Purpose

Annex G provides the requirements for welding AASHTO M 270M/M 270 (A709/A709M) Grade HPS 485W [HPS 70W] with reduced preheat using heat input and diffusible hydrogen controls for welding consumables. All provisions of the code shall apply except as modified herein. These requirements apply to joining HPS 485W [HPS 70W] to itself or to hybrid joints joining HPS 485W [HPS 70W] to lower strength materials, based on the document *Guide Specification for Highway Bridge Fabrication with HPS 70W (485W), 2nd Edition*.

G2. Filler Metal Requirements

The filler metals for matching and undermatching strength weldments shall comply with all requirements of Table G.2, with the additional requirement that the diffusible hydrogen content shall be 4 mL/100 g or less when using the preheat and interpass temperatures described in Annex Table G.2.

Consumable handling, regardless of welding process or preheat and interpass temperatures, shall be controlled in accordance with 12.6.4, 12.6.5, or 12.6.6 of this code, except that:

(1) Consumables may be handled according to the consumable manufacturer's recommendations for storage and handling procedures if they differ from those of 12.6.4, 12.6.5, or 12.6.6, and the manufacturer certifies that the diffusible hydrogen level does not exceed 4 mL/100 g using their recommendations.

(2) Consumables shall be handled according to the consumable manufacturer's recommendations for storage and handling procedures when they are more restrictive than those of 12.6.4, 12.6.5, or 12.6.6.

Fluxes for the SAW process received in undamaged, hermetically sealed containers may be used directly from the container without baking. Flux received in moisture resistant packaging shall be baked in accordance with 12.6.5.3 prior to use, consistent with the manufacturers recommendations for the maximum baking temperature.

G3. Additional NDT Testing Requirement

In addition to the testing requirements of 7.15, 7.16, and 7.17, the Procedure Qualification Record (PQR) test plate shall be ultrasonically tested (UT) in accordance with Clause 8, Inspection, Part C of this code. Evaluation must be in accordance with Table 8.4, 'UT Acceptance-Rejection Criteria—Tensile Stress', of this code. Indications found at the interface of the backing and test plates shall be disregarded, regardless of the defect rating.

G4. WPS

Welding procedure qualification of fillet welds shall be qualified using the alternative reduced preheat and interpass temperatures of Annex G.

Table G.1
Minimum Preheat and Interpass Temperature for AASHTO M 270M/M 270 (A709/A709M) HPS 485W [HPS 70W], °C [°F][a]

		Thickness of Thickest Part at Point of Welding, mm [in][b]			
Welding Process[c, d]	Diffusible Hydrogen Max.	To 20 [3/4] incl.	Over 20 to 40 [3/4 to 1-1/2] incl.	Over 40 to 65 [1-1/2 to 2-1/2] incl.	Over 65 [2-1/2]
SAW, SMAW	4 mL/100 g	10 [50]	20 [70]	20 [70]	50 [125]
FCAW, GMAW	4 mL/100 g	10 [50]	20 [70]	65 [150]	110 [225]

[a] If satisfactory results are not achieved with minimum preheat and interpass temperatures during development of the Welding Procedure Specification (WPS), and an increased preheat temperature is used to provide a satisfactory Procedure Qualification Record (PQR), the higher preheat temperature shall be the required minimum during bridge fabrication.
[b] The minimum preheat or interpass temperature required for a joint composed of different base metals and/or thicknesses shall be based on the higher of the minimum preheat required by Table 6.3 for non-HPS 485W [HPS 70W] base metal or Table G.1 above for HPS 485W [HPS 70W] base metal.
[c] Heat input for SAW shall be limited to 1.6 kJ/mm [40 kJ/in] minimum to a 3.5 kJ/mm [90 kJ/in] maximum, unless otherwise qualified.
[d] Short-circuiting and Pulsed GMAW transfer modes shall not be allowed.

Table G.2
Filler Metals for Use with the Reduced Preheat of Table G.1, Diffusible Hydrogen Levels 4 mL/100 g Maximum[a]

Welding Process	AWS Specification/Classification
Matching Strength for Joining HPS 485W [HPS 70W] Steel	
SAW	A5.23/F9A4-EXXX-XXX
FCAW	A5.29/E80T1-K2 A5.29/E90T5-K2
GMAW—Metal Core	A5.28/E90C-G
SMAW	A5.5/E9018MH4 E9018MH4R
Undermatching Strength for Joining HPS 485W [HPS 70W] Steel	
SAW	A5.17 or A5.23/F7A0-EXXX F8A0-EXXX
FCAW	A5.20/E71T-12J
SMAW	A5.1/E7018H4 E7018H4R A5.5/E8018-C3H4 E8018-C3H4R
Matching Strength for Joining HPS 485W [HPS 70W] to HPS 345W [HPS 50W] or 345W [50W] Steel	
SAW	A5.17 or A5.23/F7A0-EXXX F8A0-EXXX
SMAW	A5.1/E7018H4 E7018H4R A5.5/E8018-C3H4 E8018-C3H4R

[a] Specific manufacturer's consumables are listed in the AASHTO approved *Guide Specification for Highway Bridge Fabrication with HPS 70W (485W)*.

Annex H (Normative)
ESW Consumable Requirements

This annex is part of this standard and includes mandatory elements for use with this standard.

The current AWS A5.25/A5.25M, *Specification for Carbon and Low-Alloy Steel Electrodes and Fluxes for Electroslag Welding*, electroslag electrode specification does not address the variations of ESW-NG process modifications. This annex serves as an interim electrode specification and contains the requirements for consumables used in the ESW-NG process for both tension and compression members.

H1. Electrode

H1.1 The electrode chemical composition requirements shall be as shown in Table H.1. Chemical composition shall be evaluated not as a deposit chemical composition as required in AWS A5.25/A5.25M but by a melt button of the electrode (formed by melting cut pieces of the electrode in a crucible with an electric arc in an inert atmosphere, typically argon) or by the method given in AWS A5.28/A5.28M for chemical analysis of weld deposits for composite electrodes, shielded with 100% argon. The button or weld deposit pad shall be analyzed using a spectrometer. If spectrometer accuracy for low carbon and sulfur content is not adequate, additional analyzing of these elements may be accomplished by other methods.

H1.2 The electrode shall be analyzed for diffusible hydrogen by the GMAW process shielded by 100% argon at 40 CFH to 50 CFH. The maximum diffusible hydrogen shall be 4 mL/100 g (H4 as evaluated by AWS A4.3, *Standard Methods for Determination of the Diffusible Hydrogen Content of Martensitic, Bainitic, and Ferritic Steel Weld Metal Produced by Arc Welding*).

H1.3 Electrode chemical composition and diffusible hydrogen shall be determined per lot.

H1.4 The mechanical properties (tensile strength, yield strength, elongation, and CVN toughness) shall be determined from the PQR Test Plate and shall meet the requirements of Table 7.3.

H2. Consumable Guide

The consumable guide chemical composition requirements shall be as shown in Table H.2.

H3. Flux Moisture Content

The electroslag flux shall be evaluated for moisture content by the method given in AWS A4.4M for evaluating electrode coating and flux moisture. The moisture content shall not exceed 0.1%.

Table H.1
Required Filler Metal Chemical Composition for ESW

Element	Percent by Weight (max. unless range is given)
C	0.03
Mn	1.0–1.4
Si	0.30–0.45
Ni	2.7–3.2
Mo	0.25–0.45
Ti	0.01–0.04
Al	0.030
S	0.015
P	0.015
V	0.010
B	0.0010
Cu	0.060
Nb	0.010
Cr	0.050

Table H.2
Maximum Alloy Limits for ESW Consumable Guide

Element	Percent by Weight
C	0.06
Mn	1.0
Si	0.6
Cr	0.1
Ni	0.23
Mo	0.03
Al	0.05
Cu	0.05
Ti	0.05
S	0.02
P	0.02
V	0.010
B	0.0010
Nb	0.010

Annex I (Normative)
Guidelines for the Acceptance of Alternative ESW Processes

This annex is part of this standard and includes mandatory elements for use with this standard.

This annex applies to electroslag welding (ESW) processes to be used for members subject to tension or reversal of stress, except for the narrow-gap improved electroslag welding (ESW-NG) process approved by FHWA based on the results of extensive research and testing. Alternative processes (other than ESW-NG) shall produce welds that conform to the strength, ductility, toughness, and inspection requirements of this specification.

Additional requirements for approval are listed as follows:

(1) A proposal for acceptance of a welding process shall be accompanied by a comprehensive report describing the process in detail, including a description of all required materials and equipment, control of welding variables, and the results of all tests performed to justify the acceptance of the process.

(2) The process shall only be approved for welding grades of steel that have had successful procedure qualification tests.

(3) The process development shall include tests of welds that represent the thickest and thinnest joints to be welded, plus tests of additional representative thicknesses when the range of minimum to maximum thickness varies by 25 mm [1 in] or more. For example, when it is proposed that thicknesses from 30 mm to 100 mm [1-1/4 in to 4 in] be welded, test data shall include the results of welding various thicknesses, such as 30, 50, 75, and 100 mm [1-1/4, 2, 3, and 4 in].

(4) The test data and the report for each grade of steel welded shall include a minimum of two sets of data for each weld geometry to demonstrate the reproducibility of acceptable results.

(5) It shall be demonstrated that qualified personnel other than the original developer are able to reliably produce results that conform to the requirements of this specification by following an approved welding procedure specification.

(6) The process qualification tests shall include at least the following components:

(a) Mechanical properties of the welded joints shall be determined. Test results shall conform to the requirements of Clause 7 for the grade of steel welded.

(b) Detailed metallurgical examination and hardness traverses shall be conducted to characterize the weld, HAZ, and the base metal in all thicknesses and steels to be welded. The metallographic tests shall demonstrate that the process produces weldments that are free from grain boundary fissures and cracks in the weld and HAZ. The areas of lowest toughness shall be identified in both the weld metal and HAZ. The fusion boundaries and areas of lowest toughness in the adjacent HAZ shall be studied and reported. The CVN toughness of the weld shall conform to the requirements of this specification and the CVN toughness of the HAZ shall conform to the ASTM specification requirements for the base metal.

(c) A chemical analysis shall be made and reported for representative welds. This shall include the analysis of the base metal, filler metal, and weld asdeposited, including dilution from the base metal.

(d) ASTM E399 full-scale fracture toughness tests shall be performed on the weld and HAZ. As a minimum, tests of the weld metal shall attempt to drive the crack down the weld centerline. For the HAZ, tests shall attempt to drive the crack down the coarse grained HAZ within 1.5 mm [0.060 in] of the fusion line. Fracture toughness tests shall be conducted at the bridge loading rate of one second to full load. The test temperature shall be –20°C [0°F] for the weld metal and 5°C [40°F] for the HAZ.

(e) All weld fusion and crack defects that may result from the use of the proposed process in production shall be identified. This shall include but not be limited to lack of fusion, slag inclusion, porosity, ferrite vein cracks, hot cracks, and any surface or HAZ crack that might occur. All controls and nondestructive tests necessary to ensure that defects are not permitted to remain in bridge welds shall be listed. Any special instructions that are necessary for successful use of the process shall be provided.

(f) Radiographic and ultrasonic tests shall be performed as required in Clause 8 and as modified by the supplemental requirements for the ultrasonic inspection of electroslag welds. In addition, a thorough UT inspection shall be made using a 70° search unit with scanning movements A through E to test from Face A and B. The scanning level shall be as described in Table 8.3. All reflectors with indication ratings of up to and including +6 dB less than the reference indication shall be recorded on the test report.

(g) The results of fatigue tests on full-size bridge bending members shall be reported. The results shall demonstrate that welded components made by the proposed process conform to the general performance reliability standard demonstrated for the electroslag welds tested and reported in FHWA/RD-87-026. The specimen size, number of tests, and required results shall be as approved by the Engineer.

(7) Successful completion of the requirements described in paragraphs (1)–(6) above shall qualify the proposed ESW process to be used subject to conformance with all the provisions of this code other than the requirement to use only the ESW-NG process. Essential variable ranges shall be as established by the Engineer if Table 7.8 are not appropriate.

Annex J (Normative) Advanced Ultrasonic Examination

This annex is part of this standard and includes mandatory elements for use with this standard.

J1. Introduction

This annex provides mandatory requirements that shall apply when phased array ultrasonic testing (PAUT) is used. The alternative techniques presented in this annex require written procedures, advanced operator training and qualification, and calibration methods specific to PAUT.

J2. Scope

The procedures and standards set forth in this annex govern phased array examinations of groove welds (excluding tubular T-, Y-, and K-connection welds), including heat-affected zones (HAZ), for thicknesses between 5 mm and 100 mm [3/16 in and 4 in] using automatic data acquisition (encoded line scanning).

J3. Definitions

J3.1 Bandpass filtering. A function of the receiver circuit in most modern UT and PAUT equipment designed to filter out unwanted returned sound frequencies outside of that used for sound wave generation. The frequencies of sound on return are of much broader range than the range of frequencies put into the test piece.

J3.2 Channel. A send/receive circuit in the phased array unit. The number of channels dictates the maximum number of elements that the phased array unit can support as a whole.

J3.3 Dead elements. Individual elements that are no longer functional due to broken cables, connectors, or element failure. This can also include elements with substandard performance.

J3.4 E-Scan. A single focal law multiplexed across a grouping of active elements for a single-beam angle that is stepped along the phased array probe length in defined incremental steps.

J3.5 Element. An individual crystal (piezo-composite material) within a phased array probe.

J3.6 Encoded. Done with an encoder.

J3.7 Encoder. A device, normally in the form of a wheel, that records probe position for computer analysis for an automatic data acquisition system.

J3.8 Encoding. Using an encoder.

J3.9 Focal law. A phased array operational file defining search unit elements and time delays for transmitted and received signals.

J3.10 FSH. Full screen height.

J3.11 Imaging views. Images defined by different plane views between the ultrasonic path (ultrasonic axis), beam movement (index axis), and probe movement (scan axis) (see Figure J.1). Also called "scans" (see J3.11.1 – J3.11.5).

J3.11.1 A-Scan. A representation (view) of the received ultrasonic pulse amplitude versus time of flight in the ultrasonic path, also called a waveform.

J3.11.2 C-Scan. A 2-D plan or top view of the recorded A-scan data showing the beam movement (index axis) versus the probe movement (scan axis) path, using the maximum amplitude of the A scans at each transverse location. The C-scan may be presented in the volume-corrected or uncorrected form.

J3.11.3 Sectorial View. A 2-D view of all A-scans from a specific set of elements corrected for delay and refracted angle.

J3.11.4 Side View. A 2-D view of the recorded A-scan data for one angle showing the ultrasonic path (ultrasonic axis) along the probe movement (scan axis) path. The A-scan amplitude is color coded. The side view may be presented in the volume-corrected or uncorrected form.

J3.11.5 End view is a 2-D view which is very similar to the side view. The end view is at 90° to the side view and shows the ultrasonic path (ultrasonic axis) versus the beam movement axis (index axis).

J3.12 Line scan. The phased array scanning technique in which an E-scan, S-scan, or combination thereof, is performed with the beams directed perpendicular to the weld, at a fixed distance from the welds, in a manner demonstrated to provide full weld coverage. Also called a linear scan.

J3.13 PAUT. Phased array ultrasonic testing.

J3.14 Phased array instrument. A multichannel test instrument used with multiple-element probes that enable the application of delay/focal laws when transmitting, and receiving, before summing.

J3.15 Phased array technique. A technique wherein UT data is generated by constructive phase interference formed by multiple elements controlled by accurate time delayed pulses. This technique can perform beam sweeping through an angular range (S-scans), beam scanning at fixed angle (E-scans), beam focusing, lateral scanning, and a variety of other scans, depending on the array and programming.

J3.16 Phased array probe. A probe made up of several piezoelectric elements individually connected so that the signals they transmit or receive may be treated separately or combined as desired. The elements can be pulsed individually, simultaneously, or in a certain pattern relative to each other to create the desired beam angles or scan pattern.

J3.17 Pitch. The center to center distance between two successive phased array probe elements.

J3.18 Pulser. The instrument component that generates the electrical pulse. The number of pulsers dictates how many elements within a phased array probe may be applied within a given focal law.

J3.19 S-scan. The S-scan beam movement is a set of focal laws that provides a fan-like series of beams through a defined range of angles using the same set of elements.

J3.20 Saturated signal. A signal in which the true peak amplitude cannot be measured in the stored data file due to bit depth of the phased array system.

J3.21 Scan plan. A document specifying key process elements, such as equipment detail, focal law settings, and probe positions as necessary to complete an examination; also depicts weld and HAZ coverage.

J3.22 Scanner. A device used for holding the phased array probes in place while collecting data by means of an encoder. Scanners contain an encoder and may be automated or semiautomated types as described below.

J3.22.1 Automated scanner. A mechanized device in which the PA probe movement is computerized or driven by remote control.

J3.22.2 Semiautomated Scanner. A scanner that is manually driven along welds.

J3.23 Sound-path or depth calibration (horizontal linearity). A specific action used to compensate and adjust instrument time delay over all focal laws for specific wedge geometry for a depth or sound-path calibration.

J3.24 Time corrected gain (TCG). A calibration technique in which the search unit computes the dB gain difference needed to balance standard calibration reflectors (side drilled holes) at various material depths at one set screen amplitude. When completed, all side-drilled hole reflectors equal the same approximate amplitude regardless of their varying metal path distances.

J3.25 Virtual probe aperture (VPA). The number of elements in a phased array probe used for the examination.

J3.26 Volume-corrected scan. A presentation in which corrections are made to the index axis A-scan point locations based off true positional information relative to the beam angle or angles used during the inspection.

J3.27 VPA. Virtual probe aperture.

J4. Personnel Requirements.

J4.1 Personnel Qualification Requirements. Individuals who perform PAUT shall be certified for PAUT per 8.1.3.4. Additionally, individuals shall be certified as:

(a) UT Level II in accordance with 8.1.3.4(1) and have supplemental qualifications for PAUT; or

(b) UT Level III in accordance with 8.1.3.4(3) and have supplemental qualifications for PAUT. This includes Level III personnel who collect and analyze PAUT data.

Supplemental qualifications for PAUT shall include the following:

(1) A written test based on the PAUT requirements of this code,

(2) PAUT examinations of at least two welded joints (e.g. butt, T, corner) that contain real or artificial discontinuities to be examined using a phased array procedure written in accordance with this Annex,

(3) 320 hours of PAUT work experience.

Individuals meeting the supplemental requirements except the work experience shall have data and reports reviewed and confirmed by a UT Level II with the supplemental PAUT qualifications or UT Level III with the supplemental PAUT qualifications.

J4.2 Certification Requirements. Certification of Level II PAUT personnel shall be performed by an NDT UT Level III who both meets the requirements of 8.1.3.4 for PAUT and also has received a minimum of 80 hours of formal training in PAUT.

J5. Equipment

J5.1 Phased Array Instruments. Inspections shall be performed using phased array pulse-echo equipment meeting the requirements of 8.15, qualified in accordance with J6. Phased array instruments shall also meet the following requirements:

J5.1.1 Number of Pulsers. The instrument shall be equipped with a minimum of 16 pulsers and channels (16:16 minimum). A minimum of 16:64 is required if E-scans are to be used.

J5.1.2 Imaging Views. The phased array instrument shall be equipped with sufficient display options, including A, C, sectorial and side views, and encoded scans, to provide thorough data analysis through the entire scan length and through all beams.

J5.2 Straight-Beam (Longitudinal Wave) Probes. The straight-beam (longitudinal wave) phased array probe shall produce frequencies in the range of 1 to 6 MHz. Probe dimensions shall be small enough that standing wave signals do not appear on the display. The phased array probe shall be a linear array probe capable of providing a resolution of three side drilled holes of the RC block. Alternatively, a UT search unit meeting the requirements of 8.15.6 may be used.

J5.3 Angle-Beam Search Units. Angle-beam search units shall consist of a phased array probe and an angle wedge to produce the desired refracted angles.

J5.3.1 Phased Array Probe. The probe shall be a linear array type with a minimum of 16 elements and shall produce frequencies between 1 MHz and 6 MHz. Probe pitch dimensions shall be small enough that standing wave signals do not appear on the display.

J5.3.2 Angled Phased Array Wedge. The wedge shall be of a sufficient incident angle to produce sound beams in the material between 45° and 70° ±2°. Wedges shall be used within the angular range specified by the manufacturer.

J5.4 Encoder. The encoder shall be digital and capable of line scanning.

J5.5 Scanner. Encoding shall be performed by using a semiautomated or automated scanner as defined in J3.22.

J5.6 Couplant. A couplant material shall be used between the search unit and the test material. Any commercial couplant, water, or oil may be used when performing calibrations and examinations.

J5.7 Reference Standard for Determining SSL. The standard reflector used for test standard sensitivity level (SSL) shall be the 1.5 mm [0.06 in] diameter side drilled hole in an IIW block in conformance with ASTM E164, *Standard Practice for Contact Ultrasonic Testing of Weldments*.

J5.7.1 Supplemental Calibration Block. A supplemental calibration block shall be used allowing for a minimum of a 3-point TCG establishment throughout the usable sound-path range of all configured angles. The block shall be of sufficient thickness and length to allow calibration of reflectors throughout the entire examination volume to be tested. Each calibration block shall have at least three side drilled holes at a range of depths to cover the entire material range to be tested.

J5.7.2 Optional Mockup Verification. At the option of the PAUT operator or when required by the Engineer, detectability of the standard reflector (1.5 mm [0.06 in] side drilled hole) may be verified in a mockup or the production part. When weld mock-ups and sections of production weldments are used, the reflector shall be in locations where it is difficult to direct sound beams, thereby ensuring detection of discontinuities in all areas of interest. Mock reflectors shall be placed a minimum of 1.5 mm [0.06 in] clear distance from edges. When this verification is required, the standard reflector shall be detectable above the DRL established in J8.2.4.2. Example placements of the standard sensitivity reflector in a mockup or production part are shown in Figure J.2. If the standard reflector is not detectable, the scan plan shall be adjusted.

J6. Equipment Qualification

J6.1 System Linearity. System linearity verifications shall be validated at a maximum of 12-month intervals. Validation shall be performed as detailed in J14.

J6.2 Internal Reflections. Maximum internal reflections from each search unit shall be verified by the PAUT operator at a maximum time interval of 40 hours of instrument use and checked in accordance with 8.22.3.

J6.3 Resolution Requirements. Testing of the resolution of the combination of search unit and instrument shall be performed and documented per 8.16.3.

J6.4 Probe Operability Checks. An element operability check shall be performed by the PAUT operator prior to initial calibration and use, and weekly on each phased array probe to determine if dead (inactive) or defective elements are present. No more than 10% of the elements may be dead and in a given aperture, and no more than two adjacent elements may be dead within a given aperture. This check shall also be performed upon each 8-hour period of use. In addition, each element within a phased array probe shall be evaluated to check for comparable amplitude responses throughout the aperture. Each element shall be verified to be within 6 dB of the element yielding the highest amplitude response. If the amplitude of any of the elements within the probe yields responses outside the 6 dB requirement, the element shall be declared dead.

J6.4.1 The probe operability check shall be performed by scanning through each element with the probe on the side of an IIW block or any reference block, and observing the back wall signal.

J7. Scan Plans

J7.1 Scan Plans. A scan plan, as defined in J3, shall be developed for the welds to be examined. The scan plan shall provide the specific attributes necessary to achieve examination coverage, including those variables subject to material and geometric variation that are not addressed in a general procedure. Scan plan contents shall consider all essential variables listed in Table J.2.

J7.1.1 The scan plan shall demonstrate, by plotting or computer simulation, the appropriate refracted angles to be used during the examination for the groove weld geometry and areas of concern. The scan plan shall demonstrate coverage of the required examination volume. Performance shall be verified through the calibration (i.e., beam index point and beam angle verifications).

J7.1.2 Whenever a scan plan is developed, values of essential variables shall be established and an initial calibration performed by a PAUT Level II or III to confirm adequate sound pressure throughout the configured ultrasonic range. A new calibration shall be required if an essential variable has changed.

J7.1.3 The scan plan shall document the examination volume covered.

J7.2 Focal Law Configuration. Focal laws shall be configured to provide the necessary coverage requirements stipulated in J7.4. Focal laws shall be created using 14 to 16 elements; however, more elements may be used if additional penetration is shown to be needed during calibration. S-scans shall be used as the primary scan to optimize coverage and shall be configured in angular sweep increments of no greater than 1°. E-scans may be used as described below to supplement S-scans but shall not be used as a sole inspection technique.

J7.2.1 Index Positions. A sufficient number of index positions shall be configured to accomplish the coverage requirements of J7.4. These may be multiple physical index positions, multiple electronic index positions (grouping), or a combination of both. Scans shall contain sufficient overlap to demonstrate full coverage in the scan plan.

J7.2.2 Focusing. An unfocused (naturally focused) sound beam shall be used for scanning. Focusing may be used to better define and dimension a given indication, but shall not be used during evaluation of the indication for acceptance.

J7.2.3 Supplemental E-Scans. E-scans may be used to supplement the S-scans. When E-scans are used, a minimum overlap of 50% of each VPA shall be configured for and specified in the scan plan.

J7.2.4 Grouping. Combinations of multiple S-scans or of S-scans and E-scans may be used through grouping features to assist in joint coverage. When combined, the minimum overlap between each scan shall be 10% of coverage.

J7.3 Procedure Variables. Essential examination parameters are listed in Table J.2. All essential variables shall be documented in the scan plan. Any changes to an essential variable shall require the development of a new scan plan.

J7.4 Testing of Welds. The entire base metal, through which ultrasound must travel to test the weld, shall be tested for laminar reflectors using a straight-beam search unit conforming to J5.2. If any area of base metal exhibits total loss of back reflection or an indication equal to or greater than the original back reflection, refer to 8.19.5.

The scan plan, utilizing focal law configurations specified in J7.2, shall demonstrate full volumetric coverage in two crossing directions to cover the HAZ and the full weld volume. The weld volume coverage shall include positioning a sufficient number of offsets to include coverage as close to perpendicular to the weld fusion face as practicable for S-scans and supplemental E-scans.

All welds in butt joints examined by PAUT shall be tested from the same face on each side of the weld axis where access is possible. Welds in corner and T-joints shall be primarily tested from one side of the weld axis only. All welds shall be tested using applicable line scans or scanning patterns necessary to detect both longitudinal and transverse discontinuities.

J7.4.1 Scanning Near Edges. If edges and corners prevent access or result in other limitations for encoded PAUT, these areas may be scanned by running the scan in the opposite direction toward the edge, or by nonencoded PAUT using scanning patterns described in Clause 8. Use of nonencoded PAUT shall be noted in the examination report.

J7.4.2 Restricted Access Welds. Groove welds in butt joints that cannot be examined from both sides using the angle-beam technique shall be noted in the examination report.

J7.4.3 Backing. For joint configurations that will contain backing that is left in place, the scan plan shall consider the effects of the backing (see C-8.25.12 of AWS D1.1 for additional guidance on inspecting welds with steel backing).

J7.4.4 Inspection for Transverse Indications. Welds that are finished flush shall be inspected for transverse discontinuities using scanning pattern D as shown in Figure 8.7. Scanning pattern E shall be used on welds with reinforcement. Encoding is not required for the transverse discontinuity inspection.

J7.5 Scan Plan Storage. Scan plan parameters shall be configured on the phased array system storage and stored in a manner that will allow repeatability for subsequent examinations.

J8. Calibration for Testing

The phased array configuration as prepared in the scan plan shall be verified at intervals in accordance with 8.18.3 and as described below.

J8.1 Straight Beam Calibration. The ultrasonic range of the search unit shall be adjusted, using an E-scan at 0° set-up (or conventional straight beam probe), such that it will produce the equivalent of at least two plate thicknesses on the display. The sensitivity shall be adjusted at a location free of indications so that the first back reflection from the far side of the plate will be 80% ±5% of FSH. Minor sensitivity adjustments may be made to accommodate for surface roughness.

J8.2 Shear Wave Calibration

J8.2.1 Beam Angle Verification. The PAUT operator shall verify the beam angles to be within 2° of the minimum and maximum angles configured in S-scans or within 2° of the first and last VPAs configured for E-scans using the procedure stipulated in 8.21.2.2.

J8.2.2 Horizontal Sweep. The horizontal sweep shall be adjusted to represent the actual material path distance throughout all the configured angles using an IIW block or other alternate block as detailed in 8.16.1. The screen range shall be set at 3 times the material thickness at the minimum configured angle in the true depth display mode. If the joint configuration or thickness prevents full examination of the weld at these settings, the distance calibration shall be made at increased screen ranges as depicted in the scan plan.

J8.2.3 Time Corrected Gain (TCG). By use of the supplemental calibration block as specified in J5.7.1, a TCG shall be established throughout all configured angles at a minimum of three points throughout the material range to be tested. The TCG shall balance all calibration points within ±5% amplitude of each other.

J8.2.4 Standard Sensitivity Level (SSL). The standard sensitivity level shall be established at 50% ±5% of full screen height off of the 1.5 mm [0.06 in] reflector as specified in J5.7. This dB level shall be noted as the primary reference level dB.

J8.2.4.1 Automatic Reject Level (ARL). The ARL shall be defined as 5 dB over SSL, which equals 89% FSH (see Figure J.4).

J8.2.4.2 Disregard Level (DRL). The DRL shall be defined as 6 dB under SSL, which equals 25% FSH (see Figure J.4).

J8.3 Encoder Calibration. The encoder shall be calibrated at least weekly by the operator and verified through daily in-process checks to be within 1% of measured length for a minimum of half the total scan length. Encoder resolution shall be configured so that data is taken at 1 mm [0.04 in] increments or smaller.

J9. Examination Procedure

J9.1 X and Y. Coordinates shall be identified prior to scanning as required in 8.19.1 and 8.19.2.

J9.2 Straight Beam Scanning. Straight beam phased array examination using an E-scan at 0° shall be performed over the entire base metal area through which sound must pass. This straight beam examination may be performed using a conventional UT probe.

J9.2.1 Scanning shall be continuous over 100% of the area to be examined.

J9.2.2 When a discontinuity is observed during general scanning, the instrument shall be adjusted to produce a first reflection from the opposite side of a sound area of the plate to 80% full screen height. This instrument setting shall be maintained during evaluation of the discontinuity condition. All areas that cause a 50% reduction in the back-wall reflection or greater shall be recorded.

J9.2.3 Any indication evaluated as laminar reflectors in base material, which interfere with the scanning of examination volumes, shall require modification of the angle-beam examination technique such that the maximum feasible volume is examined, and the modification shall be noted in the record of the examination. If any area of base metal exhibits total loss of back reflection or an indication equal to or greater than the original back reflection height is located in a position that will interfere with the normal weld scanning procedure, its size and location shall be determined and reported on the UT report, and an alternate weld scanning procedure shall be used.

J9.3 Angle-Beam Scanning. Automatic computer recording of essential ultrasonic data in the manner of line scans shall be performed down the axial length of each weld. Scanning shall be performed in accordance with the documented and approved scan plan as detailed in J7.

J9.3.1 Scanning Gain. Scanning may be performed at primary reference level sensitivity as configured in J8.2.4, provided soft gain or color palette alterations are made during evaluation to aid in detection. If scanning is performed at primary reference level, soft gain shall be increased by 6dB or the color palette adjusted to end at 50% screen height during the evaluation of the weld data. If color palette adjustment or soft gain increase is not used, 6dB of additional gain over primary reference level shall be applied during scanning. For manual supplemental examinations such as for transverse discontinuity detection, scanning shall be a minimum of 6dB over primary reference level.

J9.3.2 Encoded Scanning. Except as permitted in J7.4, scanning shall be done with an encoder. Encoded line scanning shall be performed by using a mechanical fixture or apparatus to help maintain fixed index offset positioning.

J9.3.3 Scanning Speed. The indicated speed of acquisition that is established for the instrument for the given setup shall not be exceeded. If data dropout is noted, it shall not exceed 1% of the recorded data and no two consecutive lines of data shall be missed.

J9.3.4 Data Collection. The PAUT operator shall ensure that ultrasonic examination data is recorded in an unprocessed form. A full and complete data recording set of the original A-scan data with no exclusionary gating or filtering other than receiver bandpass shall be included in the data record.

J10. Evaluation

J10.1 Length Measurements. Discontinuity length shall be determined by using the 6 dB drop method described in 8.23.2. For saturated indications, in which the true peak amplitude measurement cannot be obtained, additional scans at lower gain levels shall be performed for Class B and C discontinuities with near rejectable lengths or proximities to adjacent indications or weld intersections where applicable. The length may be determined from the stored data file.

J10.2 Acceptance Criteria. Welds shall be acceptable provided they have no cracks, nor any indications whose amplitude or length exceed that specified in Table J.3 for the applicable type of loading. Discontinuities shall be classified based on their maximum amplitude of their indications in accordance with Table J.1 (also see Figure J.4).

Manual PAUT may be used to supplement the scan in order to determine whether a discontinuity is a crack.

Indications characterized as cracks shall be considered unacceptable regardless of length or amplitude.

Class B and C discontinuities shall be separated by at least 2L, L being the length of the longer discontinuity, except that when two or more such discontinuities are not separated by at least 2L, but the combined length of discontinuities and their separation distance is equal to or less than the maximum allowable length under the provisions of Class B or C, the discontinuities shall be considered a single acceptable discontinuity.

Class B and C shall not begin at a distance less than 2L from the weld ends carrying primary tensile stresses, L being the discontinuity length.

For Class C, determination of depth of discontinuity shall be determined by the location of the peak amplitude, at the angle producing the maximum signal amplitude.

J10.3 Repair. Repairs to welds found unacceptable by PAUT shall be made in accordance with 5.7. Repaired areas shall be retested using the same scan plan and techniques as used for the original inspection, unless the scan plan does not provide coverage of the repaired area. In this case, a new scan plan shall be developed for the repair area. The minimum length of the repair that shall be reinspected shall be the length of the gouge plus 50 mm [2 in] on each end.

J11. Data Analysis

J11.1 Validation of Coverage. Recorded data shall be assessed to ensure full execution of the scan plan over 100% of the required examination length.

J11.2 Data Analysis and Recording Requirements. The following are requirements for evaluation of data:

(1) The entire exam volume shall be analyzed, using gates and available cursors, to locate and identify the source, location, and nature for all indications. Alternately, manual plotting may be used to augment on-board analysis, e.g., nonparallel or inconsistent geometries.

(2) Responses resulting from weld root and weld cap geometries shall be investigated and the basis for this classification should be noted on the report form.

(3) Any indication warranting evaluation shall be recorded to support the resultant disposition. The extent of recording shall be sufficient for reviewers and subsequent examiners to repeat the result and should stand alone as a written record.

(4) Rejectable indications shall be reported. The report shall include peak amplitude, indication rating, length of indication, depth below the surface, and relative position to provide adequate information for the repair. Cursor placement, measurement features, and annotations and comments shall clearly support disposition.

(5) For welds designated in the contract documents as being Fracture Critical, indication ratings up to and including 6 dB less critical (higher) than acceptance levels shall be recorded on the test report for informational purposes.

J12. Data Management

J12.1 Data Management System. There shall be a data management scheme established consistent with job requirements and size.

J12.2 File Nomenclature. A systematic file naming scheme shall be used to control data management of calibration and set-up files, phased array data files, and digitally generated data report forms.

J12.3 Raw Data. All phased array data shall be saved in the original raw A-scan format.

J12.4 Data Reviewing. Any review and evaluation of the phased array data shall not change or affect the original A-scan data.

J13. Documentation and Reporting

J13.1 Reporting. Examination reports shall meet the requirements of 8.20 and may be output from the on-board reporting feature of the phased array unit provided all necessary information is included. Reports may also be produced in the written manual UT conventional format or by external computer-generation.

If PAUT is being substituted for RT, the written report shall include, at a minimum, encoded C-scans covering the entire length inspected and A, C, sectorial, and side views (see J3.11) of all reportable indications. All raw data for PAUT substituted for RT shall be retained for the same duration required for radiographic film.

J13.2 Repairs. Results from PAUT inspections of repaired welds shall be tabulated on the original form (if available) or additional report forms, and shall be indicated by the appropriate repair number (R1, R2, R3, etc.)

J13.3 Scan Plan Reporting. The scan plan used during inspection shall accompany the report form.

J14. System Linearity Verification

J14.1 General Requirements. Linearity verifications shall be conducted at a minimum of every 12 months and recorded on a form similar to that shown in Table J.4. The verifications shall be conducted by a PAUT Level II or III, or at the Contractor's option, the equipment may be sent to the manufacturer for verification.

J14.1.1 The phased array instrument shall be configured to display an A-scan presentation.

J14.1.2 The time base of the A-scan shall be adjusted to a suitable range to display the pulse-echo signals selected for the particular linearity verification to be performed. A standard IIW or other linearity block similar to that described in ASTM E317, *Standard Practice for Evaluating Performance Characteristics of Ultrasonic Pulse-Echo Testing Instruments and Systems without the Use of Electronic Measurement Instruments*, shall be selected to provide signals to assess linearity aspects of the instrument (see Figure 8.5).

J14.1.3 Pulser parameters shall be selected for the frequency and bandpass filter to optimize the response from the probe used for the linearity verifications.

J14.1.4 The receiver gain shall be set to display nonsaturating signals of interest for display height and amplitude control linearity assessments.

J14.2 Display Height Linearity Verification Procedure

(1) With the phased array instrument connected to a probe (shear or longitudinal) and coupled to any block that will produce two signals, the probe shall be adjusted such that the amplitude of the two signals are at 80% and 40% of the display screen height.

(2) The gain shall be increased using the receiver gain adjustment to obtain 100% of full screen height of the larger response. The height of the lower response is recorded at this gain setting as a percentage of full screen height.

(3) The height of the higher response shall be reduced in 10% steps to 10% of full screen height and record the height of the second response for each step.

(4) The larger signal shall be returned to 80% to ensure that the smaller signal has not drifted from its original 40% level due to coupling variation. Repeat the test if variation of the second signal is greater than 41% or less than 39% full screen height.

(5) For an acceptable tolerance, the responses from the two reflectors shall bear a 2-to-1 relationship to within ±3% of full screen height throughout the range 10% to 100 % (99% if 100% is saturation) of full screen height.

(6) The results shall be recorded on an instrument linearity form as shown in Table J.4.

J14.3 Amplitude Control Linearity Verification Procedure

Each of the pulser-receiver components shall be checked to determine the linearity of the instrument amplification capabilities. For instruments configured to read amplitudes greater than can be seen on the display, a larger range of checkpoints may be used. For these instruments, the gated output instead of the A-scan display shall be verified for linearity.

(1) A flat (normal incidence) linear array phased array probe shall be selected having at least as many elements as the phased array ultrasonic instrument has pulsers.

(2) The phased-array ultrasonic instrument shall be configured using this probe to have an E-scan at 0°. Each focal law will consist of one element. The scan will start at element number 1 and end at the element number that corresponds to the number of pulsers in the phased-array instrument.

(3) The probe shall be coupled to a suitable surface to obtain a pulse-echo response from each focal law. The backwall echo from the 25 mm [1 in] thickness of the IIW block or similar block provides a suitable target option. Alternatively, immersion testing may be used.

(4) Channel 1 of the pulser-receivers of the phased-array instrument shall be selected. Using the A-scan display, monitor the response from the selected target. Adjust the gain to bring the signal to 40% screen height.

(5) The gain shall be added to the receiver in the increments of 1 dB, then 2 dB, then 4 dB, and then 6 dB. Remove the gain added after each increment to ensure that the signal has returned to 40% display height. Record the actual height of the signal as a percentage of the display height.

(6) The signal shall be adjusted to 100% display height, remove 6 dB gain and record the actual height of the signal as a percentage of the display height.

(7) Signal amplitudes shall fall within a range of +/– 3% of the display height required in the allowed height range of Table J.4.

(8) The sequence from (4) to (7) shall be repeated for all other pulser-receiver channels and record results on a linearity report form as shown in Table J.4.

J14.4 Time-Based Linearity (Horizontal Linearity) Verification Procedure

(1) The phased array instrument shall be configured to display an A-scan presentation using a 250 mm [10 in] range.

(2) Any longitudinal (compression) wave probe shall be selected and the phased-array instrument shall be configured to display a range obtaining at least ten multiple back reflections from the 25 mm [1 in] wall thickness of the calibration block.

(3) The phased-array instrument shall be set to an analog-to-digital conversion rate of at least 80 MHz.

(4) With the probe coupled to the block and the A-scan displaying 10 clearly defined multiples as illustrated in Figure J.5, the display software shall be used to assess the interval between adjacent backwall signals.

(5) The acoustic velocity of the test block shall be set by calibration (ASTM E494 may be used as a guide), the acoustic velocity in the display software shall be entered, and the display shall be configured to read out in distance (thickness).

(6) Using the reference and measurement cursors, the interval between each multiple shall be determined and the interval of the first 10 multiples shall be recorded.

(7) Each intermediate trace deflection shall be correct within 2% of the screen width.

J15. Background References

J15.1 ASTM E494, *Standard Practice for Measuring Ultrasonic Velocity in Materials*

J15.2 ASTM E2491, *Standard Guide for Evaluating Performance Characteristics of Phased-Array Ultrasonic Examination Instruments and Systems*

J15.3 ASTM E2700, *Standard Practice for Contact Ultrasonic Testing of Welds Using Phased Arrays*

J15.4 ISO 2400, *Non-destructive testing – Ultrasonic examination specification for calibration block No. 1*

Table J.1
Discontinuity Classification

Discontinuity Classification	Description[a]
A	> ARL
B	> SLL, ≤ ARL
C	> DRL, ≤ SLL
D	≤ DRL

[a] See J8.2.4.

Table J.2
Essential Variables for PAUT (see J7.1 and J7.3)

Element numbers used for focal laws
Angular range of S-scan
Manufacturer's documented permitted wedge angular range
Weld configurations to be examined, including thickness dimensions and base material product form (pipe, plate, etc.)
Surface curvature along index axis (e.g., for longitudinal weld in tubular member)
The surfaces from which the examination is performed
Techniques (straight beam, angle beam, contact)
Search unit types, frequencies, element sizes and shapes
Phased array units
Manual vs. automated/semiautomated scanning
Method for discriminating geometric from weld defect indications
Decrease in scan overlap
Method for determining focal/delay laws if other than on-board equipment algorithms included in the software revision specified
Acquisition or analysis software type
Probe manufacturer and model
Any increase in scanning speed
Couplant, if not listed in 8.19.4
Computer enhanced data analysis

Table J.3
PAUT Acceptance Criteria (see J10.2)

Maximum Discontinuity Amplitude Level Obtained	Maximum Discontinuity Lengths by Type of Loading	
	Compression	Tension
Class A (> ARL)	None allowed	None allowed
Class B (> SLL, ≤ ARL)	20 mm [3/4 in]	12 mm [1/2 in]
Class C (> DRL, ≤ SLL)	50 mm [2 in]	Middle half of weld: 50 mm [2 in] Top or bottom quarter of weld: 20 mm [3/4 in]
Class D (≤ DRL)	Disregard	Disregard

Table J.4
Linearity Verification Report Form (see J14)

Location:		Date:	
Operator:		Signature:	
Instrument:		Couplant:	
Pulser Voltage (V):	Pulse Duration (ns):	Receiver (band):	Receiver Smoothing:
Digitization Frequency (MHz):		Averaging	

Display Height Linearity			Amplitude Control Linearity		
Large %	Small Allowed Range %	Small Actual %	Ind. Height %	dB	Allowed Range %
100	47–53		40	+1	42–47
90	42–48		40	+2	48–52
80	40	40	40	+3	60–66
70	32–38		40	+4	77–83
60	27–33		40	+6	47–53
50	22–28				
40	17–23				
30	12–18				
20	7–13				
10	2–8				

Amplitude Control Linearity Channel Results: (Note any channels that do not fall in the allowed range)

Channel (Add more if required for 32 or 64 pulser-receiver units)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Time Based (Horizontal) Linearity (for 25 mm [1 in] IIW Blocks)

Multiple	1	2	3	4	5	6	7	8	9	10
Thickness	25 mm [1 in]	50 mm [2 in]	75 mm [3 in]	100 mm [4 in]	125 mm [5 in]	150 mm [6 in]	175 mm [7 in]	200 mm [8 in]	225 mm [9 in]	250 mm [10 in]
Measured Interval										
Allowed deviation (Yes/No)										

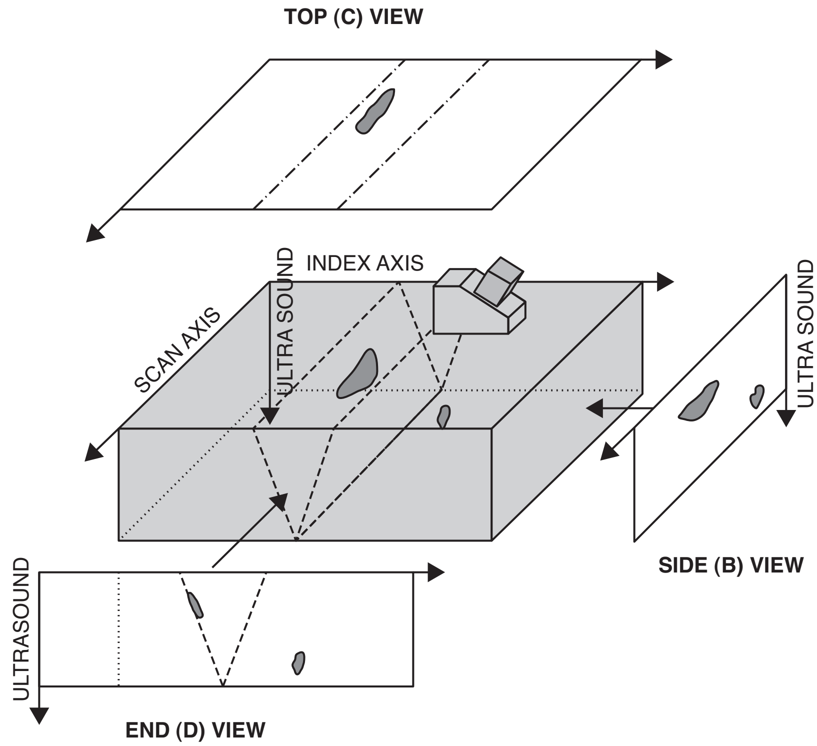
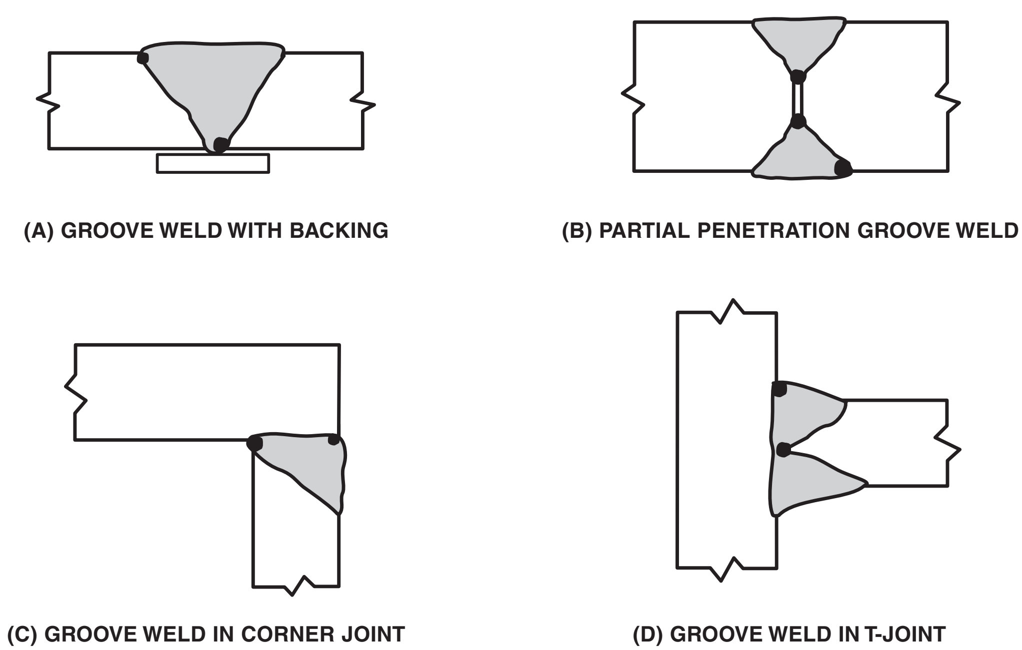


Figure J.1—Phased Array Imaging Views (see J3.11)



Source: Adapted from AWS D1.1/D1.1M:2015, *Structural Welding Code—Steel*, Figure O.3, American Welding Society.

Figure J.2—Example Standard Reflector Locations in Weld Mockup (see J5.7)

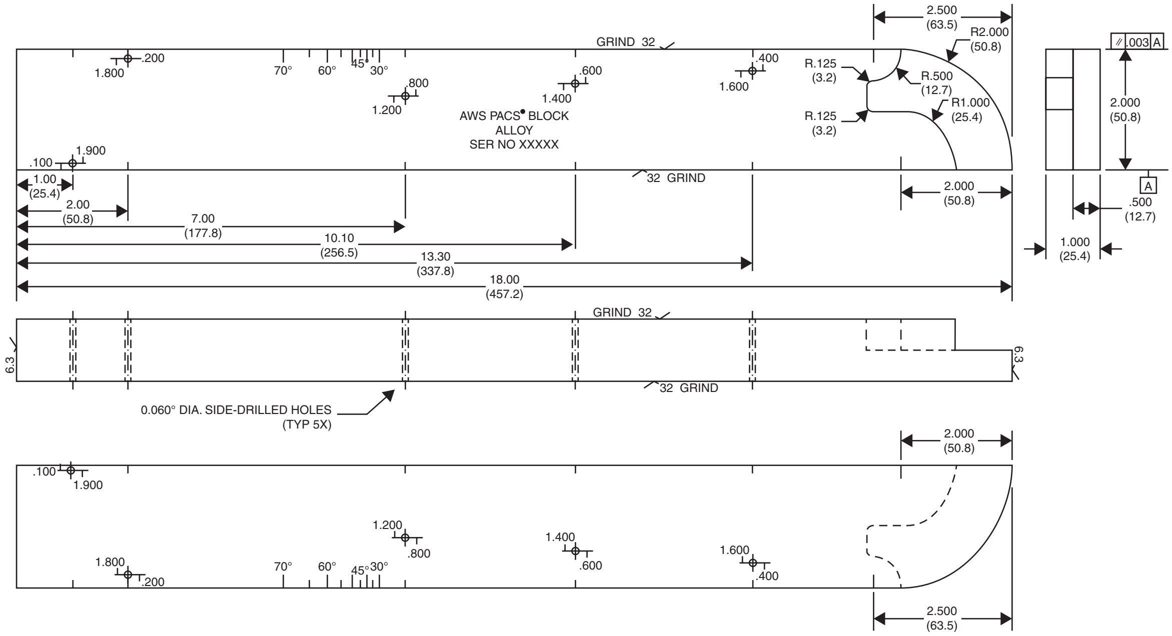


Figure J.3—Example Phased Array Calibration Standard (PACS) Type Block (see J5.7.1)

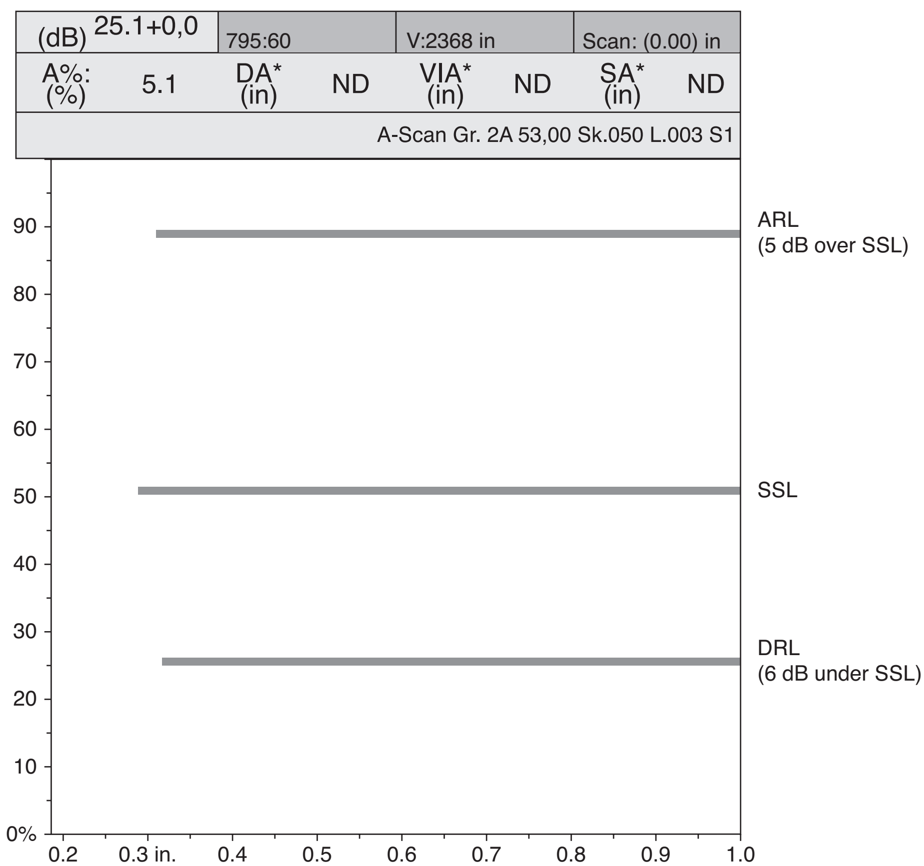


Figure J.4—Sensitivity Levels (see J8.2.4 and J10.2)

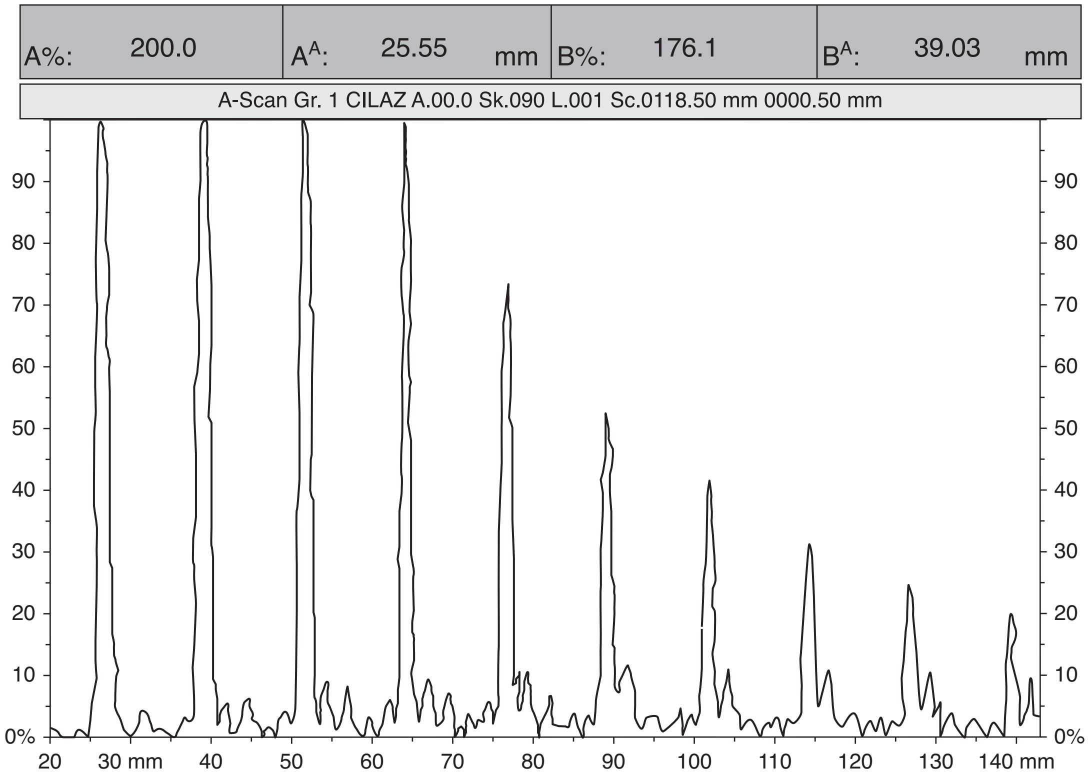


Figure J.5—Example of Time-Based Linearity Verification (see J14.4)

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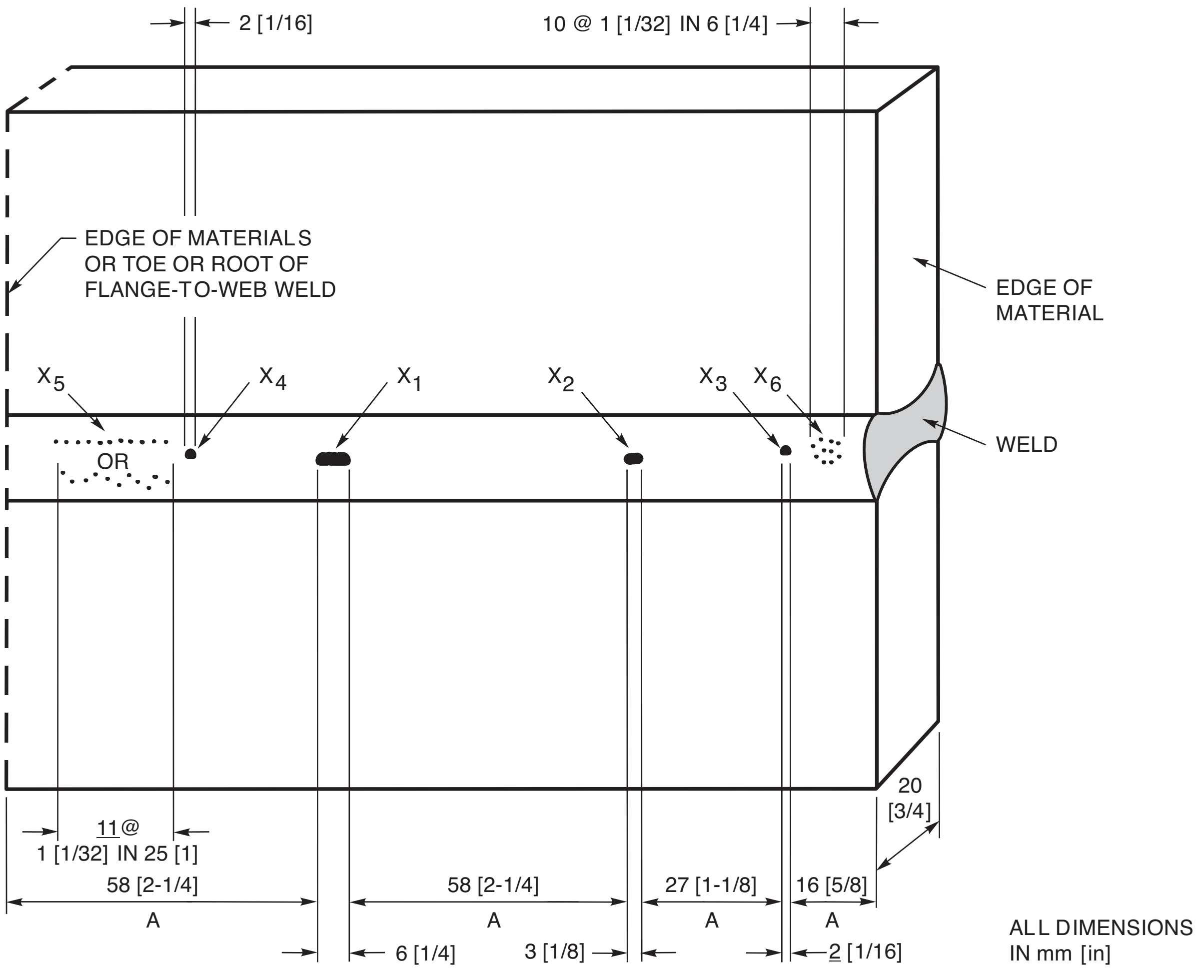
Annex K (Informative)
Weld Quality Requirements for Tension Joints

This annex is not part of this standard but is included for informational purposes only.



Notes:

1. A—minimum clearance allowed between edges of porosity or fusion-type discontinuities 2 mm [1/16 in] or larger. Larger of adjacent discontinuities governs.
2. X_1—largest allowable porosity or fusion-type discontinuity for 20 mm [3/4 in] joint thickness (see Figure 8.8).
3. X_2, X_3, X_4—porosity or fusion-type discontinuity 2 mm [1/16 in] or larger, but less than maximum allowable for 20 mm [3/4 in] joint thickness.
4. X_5, X_6—porosity or fusion-type discontinuity less than 2 mm [1/16 in].
5. Discontinuity size indicated is assumed to be its greatest dimension.
6. Porosity or fusion-type discontinuity X_4 is not acceptable because it is within the minimum clearance allowed between edges of such discontinuities (see 8.26.2.1 and Figure 8.8). Remainder of weld is acceptable.

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Annex L (Informative)
Description of Common Weld and Base Metal Discontinuities (Reprinted with modification from New York State Steel Construction Manual)

This annex is not part of this standard but is included for informational purposes only.

L1. General

This annex describes discontinuities that may or may not be classified as unacceptable under the provisions of this code. Except for cracks, discontinuities are unacceptable only if they exceed the specification requirements for type, size, distribution, or location. All cracks are unacceptable discontinuities under the provisions of this code. Discontinuities may be found in the base metal, weld metal, or heat-affected zones (HAZs) in butt, T-, corner, and lap-joint configurations. The following articles present a fairly comprehensive list of discontinuities which may be encountered in fabrication.

L2. List of Discontinuities

The most common types of discontinuities found in butt, T-, corner, and lap joints are described in Table L.1 and shown in Figures L.1 through L.6.

Weld and base metal discontinuities of specific types are more common when certain welding processes and joint details are used. High restraint and limited access to portions of a weld joint preparation may lead to a higher than normal incidence of weld and base metal discontinuities.

Each general type of discontinuity is discussed in detail in this annex. The *New York State Steel Construction Manual*, the AWS *Structural Welding Code—Steel*, and this *Bridge Welding Code* use the term *fusion-type discontinuity* as an all-encompassing term to describe slag inclusions, incomplete fusion, inadequate joint penetration, and similar generally elongated discontinuities in weld fusion.

As this code requires all CJP welds without backing to be backgouged to sound metal before welding from the second side, inadequate joint penetration is technically impossible if all provisions of the code are met. Many codes consider fusion discontinuities less critical than cracks. The *Bridge Welding Code* reflects our agreement with this provision. Some codes specifically prohibit not only cracks but also any area of incomplete fusion or inadequate joint penetration. This code does not prohibit incomplete fusion or inadequate joint penetration, per se, even though these are planar discontinuities that in a fracture analysis will perform in a manner similar to cracks. Incomplete fusion and inadequate joint penetration are treated as fusion discontinuities since they generally do not have the tip acuity of a crack, and because routine NDT generally cannot distinguish between the various types of fusion discontinuities.

Specific joint types and WPSs may have an effect on the type, location, and incidence of discontinuities. The conditions that may effect the formation of discontinuities are described in the following articles.

L2.1 Porosity. Porosity is created when gas is entrapped in solidifying metal. The discontinuity formed is generally spherical but may be elongated. When there are gas discontinuities in ingots that are reduced to wrought products, gas voids in the ingot will appear as laminations in the finished product. This annex only discusses porosity as a weld discontinuity. Unless porosity is gross (large or extensive, or both), it is not as critical as sharp, planar discontinuities that intensify stress. Porosity is a sign that the welding process is not being properly controlled or that the base metal is contaminated or of variable composition. Porosity is not caused exclusively by hydrogen, but the presence of porosity indicates that there is a possibility of hydrogen in the weld and HAZ that may lead to cracking.

(1) *Uniformly Scattered Porosity.* Uniformly scattered porosity is scattered pores distributed through a single weld pass, or throughout several passes of a multiplepass weld. Whenever uniformly scattered porosity is encountered, the case is generally faulty welding technique or materials. Porosity will only be present in a weld if the technique used, materials, or the conditions of the weld joint preparation lead to gas formation and entrapment. If the weld cools slowly enough to allow gas to pass to the surface before the weld solidifies, there will be no porosity in the weld.

(2) *Cluster Porosity.* Cluster porosity is a localized grouping of pores that usually results from improper initiation or termination of the welding arc.

(3) *Linear Porosity.* Linear porosity is porosity aligned along a joint boundary, the root of the weld, or an interbead boundary. Linear porosity is caused by contamination that leads to gas evolution at particular locations within the weld.

(4) *Piping Porosity.* Piping porosity is a term for elongated (cylindrical) gas discontinuities. Piping porosity in fillet welds extends from the root of the weld towards the surface of the weld. When one or two porosity discontinuities are seen on the surface of the weld, careful excavation will generally show that there are many subsurface piping porosity discontinuities interspersed among the exposed pores. Much of the piping porosity found in welds does not extend all the way to the surface. Piping porosity in electroslag and electrogas welds can become very extensive in number and length. Pores as long as 500 mm [20 in] have been measured in some ESW welds. Piping porosity is very difficult to evaluate by UT.

L2.2 Inclusions

(1) *Nonmetallic Slag.* Slag inclusions result from nonmetallic, solid material being entrapped in weld metal, between weld passes, or between weld and base metal. Slag inclusions can be found in welds made by most arc WPSs. In general, slag inclusions result from faulty welding technique, failure to clean properly between weld passes, and conditions that lead to limited access for welding within the joint. If allowed, molten slag will float to the top of the weld. Sharp notches in joint boundaries or between weld passes often cause slag to be entrapped under the molten weld metal.

(2) *Metallic Tungsten.* Tungsten inclusions are found only in welds made by the gas tungsten arc welding (GTAW) process. Since this process is not used under the provisions of this code, the discontinuity is described for interest only. Tungsten inclusions may be found in aluminum welds made by the GTAW process. A nonconsumable tungsten electrode is used to establish a welding arc between the electrode and the base metal. If the tungsten electrode is dipped into the molten metal, or if the current is set too high, tungsten droplets may be transferred from the electrode to the molten metal. Tungsten inclusions appear as light marks or areas in radiographs because the inspecting radiation has a higher absorption rate in tungsten than it does in steel or aluminum.

L2.3 Incomplete Fusion. Incomplete fusion may result from improper welding techniques, improper preparation of material for welding, or improper joint design. Deficiencies causing incomplete fusion include insufficient welding heat, improper electrode manipulation, and lack of access to all boundaries of the weld joint that are to be fused during welding. On rare occasions, weld metal may fail to fuse to the base metal even though the prepared joint surface has been melted beyond the original interface. Tightly adhering oxides will interfere with complete fusion, even when there is access for welding and proper welding procedures are used.

L2.4 Inadequate Joint Penetration. Inadequate joint penetration is penetration of the welding arc that is less than required. Technically, this discontinuity can only be present when the WPS requires penetration of the weld metal beyond the original joint boundaries and the weld deposit fails to penetrate the areas of weld joints that depend on penetration for fusion. Inadequate joint penetration may result from insufficient welding heat, improper electrode manipulation or guidance, or improper joint design that requires melting of more base metal than the arc can penetrate. Some WPSs have much greater penetrating ability than others.

This code requires that all CJP groove welds without backing be backgouged to sound metal before welding from the second side so that there is no possibility of inadequate joint penetration at the root of the weld. In bridge construction, weld joint designs calling for a specific root penetration that would produce CJP groove welds are not used.

L2.5 Undercut. Undercut considered to be a defect is generally the result of either an improper welding technique, excessive welding heat, or both. It is generally located at the junction of the weld and base metal, at the toe of fillet welds, or at the fusion line of groove welds. Undercut may also be encountered at the root of groove welds made from one side only. The most serious undercut is generally found in base metal surfaces that were vertical during welding. Undercut creates a mechanical notch at the fusion boundary of the weld. All welds have some undercut if examined carefully. Undercut shall not be considered an unacceptable weld discontinuity until the degree of undercutting exceeds the amount allowed by contract documents. Some undercut produces a sharp notch defect. Other undercutting may be more rounded. Some undercut may only be seen in metallographic tests where etched weld cross sections are examined under magnification. The sharper and deeper the notch created by undercutting, the more serious the defect.

L2.6 Underfill. Underfill is a depression on the face of the weld extending below the surface of the adjacent base metal. Underfill results from failure of the welder or welding operator to completely fill the weld joint as required by the WPS.

L2.7 Overlap. Overlap is a sharp surface connected discontinuity that forms a severe mechanical notch because the weld metal protrudes or flows beyond the toe or face of the weld without fusion. It can occur as a result of failure to control the welding process, improper selection of welding materials, or improper preparation of the base metal prior to welding. Tightly adhering oxides on the base metal may interfere with fusion, and overlap may result.

L2.8 Laminations. Laminations are planar discontinuities elongated in the rolling direction. These are most commonly found near the mid thickness of wrought products. Laminations may be completely internal and detectable only by NDT, or they may extend to an edge or end where they are visible at the surface. Laminations may be discovered when cutting or machining exposes internal metal structure.

Laminations are formed when gas voids (porosity), nonmetallics, or ingot shrinkage cavities are rolled flat. Laminations generally run parallel to the surface of rolled products and are most commonly found in shapes and plates. Some laminations are partially roll-forge welded along their interface by the high temperature and pressure of the rolling or forging operation. The soundness of the roll-forged weld depends on the presence or absence of oxides or nonmetallics on the surfaces of the original voids. Laminations that are partially or completely roll-forge welded may conduct sound across the interface and therefore may not be accurately evaluated by UT. Metals containing laminations generally cannot be relied upon to transmit tensile stresses in the throughthickness direction. Laminations may be a source of gas voids and cracks in adjacent butt welds.

L2.9 Delamination. Delamination is the separation of a partially or completely roll-forge welded lamination under stress. The stress may be residual stress from welding or applied stress. Delaminations may be found visually at the edges or ends of pieces or may be discovered by UT.

L2.10 Seams and Laps. Seams and laps are longitudinal base metal discontinuities that may be found in rolled products. When seams and laps are located parallel to the principal stress, they are generally not considered unacceptable discontinuities. When seams or laps are perpendicular to the applied or residual stresses, these will often propagate as cracks. Seams and laps are surfaceconnected discontinuities that result from cracks in the surface of the ingot or mechanical deformations caused by the manufacturing process. These discontinuities are modified during rolling so that the bottom of a seam is generally not so sharp as the original ingot- or slabcrack. These may be masked by mill scale or by the surface texture of the finished product. Welding over seams and laps can lead to cracking.

L2.11 Lamellar Tears. Lamellar tears are somewhat terrace-like separations in the base metal adjacent to the HAZ, typically caused by thermally induced shrinkage stresses resulting from welding. Lamellar tearing is a form of fracture resulting from high stress in the short-transverse (through-thickness) direction that may extend over long distances. The tears are roughly parallel to the surface of the rolled product and generally initiate in regions of the base metal having a high incidence of coplanar, stringer-like nonmetallic inclusions. These inclusions are usually manganese sulfides in areas of the base metal subject to high-residual stress. The fracture usually propagates from one lamellar plane to another by shear along lines that are roughly normal to the rolled surface. Lamellar tearing is exacerbated by hydrogen and may be thought of as a form of hydrogen cracking. Low-sulfur steels and steels with controlled sulfur morphology have improved resistance to lamellar tearing.

L2.12 Cracks. Weld and base metal cracks exclusive of fatigue cracks occur in weld and base metal when localized stresses exceed the ultimate strength of the material. Cracking is generally associated with stress amplification near discontinuities in welds and base metal, or near mechanical notches associated with weldment design. High residual stresses are generally present, and hydrogen embrittlement is often a contributor to crack formation. Welding-related cracks are generally brittle in nature, exhibiting little plastic deformation at the crack boundaries.

Cracks can be classified as either hot or cold cracks. Hot cracks develop at elevated temperatures. These commonly form upon solidification of the metal at temperatures near the melting point. Cold cracks, sometimes called *delayed cracks* or *hydrogen cracks,* can form hours and even months after the completion of welding and are commonly associated with hydrogen embrittlement. Cold cracks propagate both between and through the grains. Cracks may be termed longitudinal or transverse, depending on their orientation. All cracks result from tensile stress, which may be a combination of residual, secondary, and applied stress. Crack initiation and propagation is greatly influenced by the presence of discontinuities that concentrate stress.

L2.12.1 Longitudinal Cracks. When a crack is parallel to the axis of the weld, it is called a longitudinal crack regardless of whether it is along the centerline of the weld metal, or in the HAZ of the base metal. Longitudinal cracks in submerged arc welds, made by automatic welding procedures, are often associated with high welding speeds and sometimes are aggravated by segregation of weld metal constituents or by extensive porosity that does not show on the surface of the weld. Longitudinal cracks in small welds between heavy sections are often the result of high cooling rates and high restraint.

L2.12.2 Transverse Cracks. Transverse cracks are perpendicular to the axis of the weld. They may be in weld metal, base metal, or both. Transverse cracks may be limited in size and contained completely within the weld, or may propagate from the weld metal into the adjacent HAZ and into the unaffected base metal. Transverse cracks initiating in weld metal are commonly the result of longitudinal shrinkage stresses acting on excessively hard (brittle) weld metal. Transverse cracks initiating in the HAZ are generally hydrogen cracks.

L2.12.3 Crater Cracks. Crater cracks are cracks that form in the crater or depression that is formed by improper termination of the welding arc. Crater cracks are shallow, hot cracks that usually form a multipointed starlike cluster, although they may have other shapes.

L2.12.4 Throat Cracks. Throat cracks are longitudinal cracks that are generally located in the center of the weld bead. These are generally, but not always, hot cracks.

L2.12.5 Toe Cracks. Toe cracks are generally cold cracks. These initiate or propagate from the toe of the weld where restraint stresses are highest. Toe cracks initiate approximately normal to the base metal surface but more accurately normal to the tensile stress acting at that location and propagate to various depths in the base metal depending on the residual stress and toughness of the base metal.

L2.12.6 Root Cracks. Root cracks are generally longitudinal cracks in the root of the weld. Root cracks are generally hot cracks.

L2.12.7 Underbead and HAZ Cracks. Underbead and HAZ cracks are almost always cold cracks that form in the HAZ. These are generally short cracks but may join to form much larger continuous cracks. Underbead and HAZ cracks generally align themselves with weld boundaries that concentrate residual stresses. Underbead cracking and all other hydrogen cracks can become a serious problem when three elements are present: a susceptible microstructure, high residual stress, and hydrogen.

L2.12.8 Fissures. The term *fissure* is used to describe small to moderate size separations along prior austenite grain boundaries. This discontinuity is commonly found in electroslag and electrogas welds. Fissures occur in other welds, but they are easier to detect in ESW welds because of the much larger prior austenite grain size. When ESW welds are subject to high restraint, and hydrogen is present, fissuring may become a major problem. Fissuring in ESW and EGW welds is generally restricted to the center portion of the weld that is subject to high tensile residual stress resulting from solidification. Fissures can be either hot or cold cracks, although cold cracking is more common. The term *microfissure* is used for cracks that are so small that magnification must be used to detect the separation. The term *macrofissure* is used when the separation is large enough to be seen with the unaided eye.

L2.13 Fatigue Cracks. Fatigue cracks are different from the cracks described in L2.12 of this annex in that they represent cumulative damage from repeated applications of load. Fatigue cracks may extend preexisting cracks of any origin or may develop as new cracks from stress concentrations resulting from weld discontinuities or structural details.

The process of fatigue cracking left unchecked can propagate subcritical cracks to critical size at which point, brittle fracture will occur. The difference between weld quality standards for buildings and those specified for bridges is based on the knowledge that bridge members subject to significant stress range and cycles of load are subject to fatigue crack initiation and growth; statically loaded structures are not.

Fatigue life of a structural member is the sum of initiation life plus propagation life until critical crack size is reached and failure occurs. Initiation life is generally much greater than propagation life, so it is essential that structures not be placed in service with known preexisting cracks (see *Fracture and Fatigue Control in Structures—Applications of Fracture Mechanics*, 2nd Edition, by Barsom and Rolfe, Prentice-Hall Inc.).

Table L.1
Common Types of Discontinuities (see L2)

Type of Discontinuity	Location	Remarks
1) Porosity a) Uniformly scattered b) Cluster c) Linear d) Piping	W	Weld only, as discussed herein. (Porosity is also commonly found in castings.)
2) Inclusions a) Nonmetallic slag b) Metallic tungsten	W	
3) Incomplete fusion (also called lack of fusion)	W	Found at joint boundaries or between passes.
4) Inadequate joint penetration (also called lack of joint penetration)	W	Found at root of weld preparation.
5) Undercut	BM	Found at junction of weld and base metal at surface.
6) Underfill	W	Found at outer surface of joint penetration.
7) Overlap	W	Found at junction of weld and base metal at surface.
8) Laminations	BM	Found in base metal, generally near mid-thickness of section.
9) Delamination	BM	Found in base metal, generally near mid-thickness of section.
10) Seams and laps	BM	Found at base metal surface. Almost always longitudinal.
11) Lamellar tears	BM	Found in base metal near weld HAZ.
12) Cracks		
a) Longitudinal	W, HAZ, BM	Found in weld or base metal adjacent to weld fusion boundary.
b) Transverse	W, HAZ, BM	Found in weld (may propagate from weld in HAZ and base metal).
c) Crater	W	Found in weld at point where arc is terminated.
d) Throat	W	Found at weld axis.
e) Toe	HZ	Found at junction between face of weld and base metal.
f) Root	W	Found in weld metal at root.
g) Underbead and HAZ	HAZ	Found in base metal in HAZ (may propagate into unaffected base metal).
h) Fissures	W	Found in weld metal.

W — Weld
BM — Base Metal
HAZ — Heat-Affected Zone

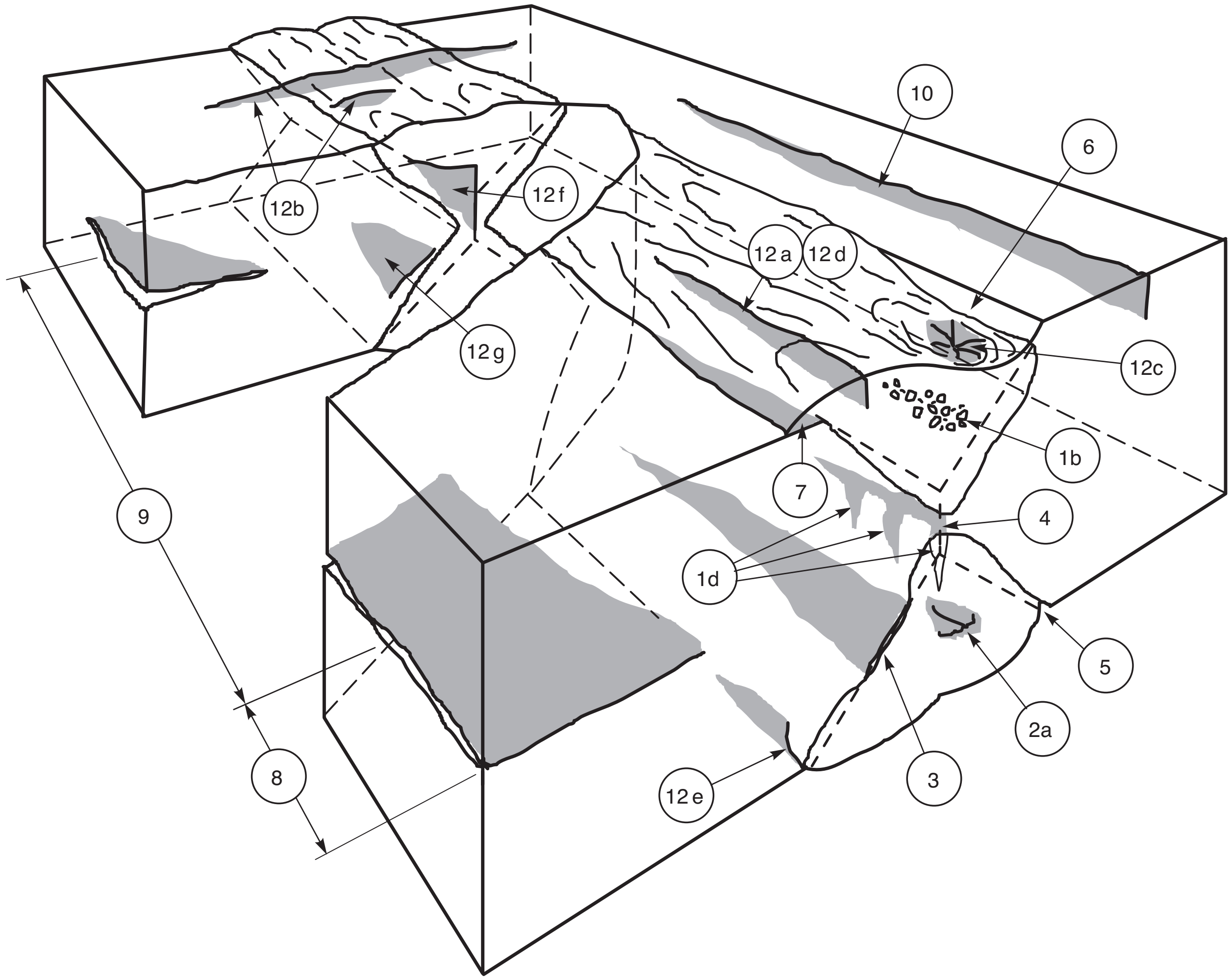

Figure L.1—Weld in Butt Joint (see L2)

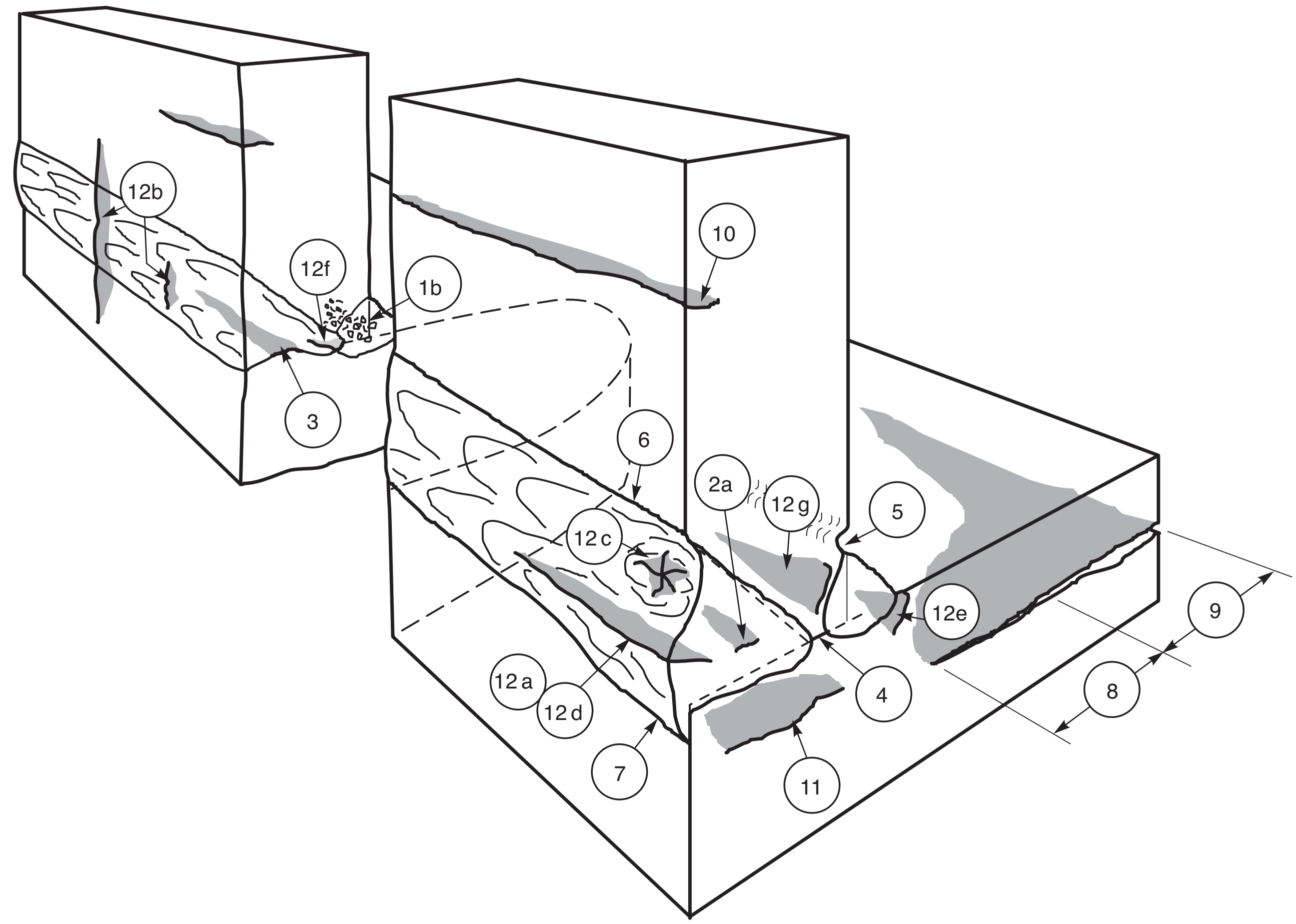

Figure L.2—Weld in Corner Joint (see L2)

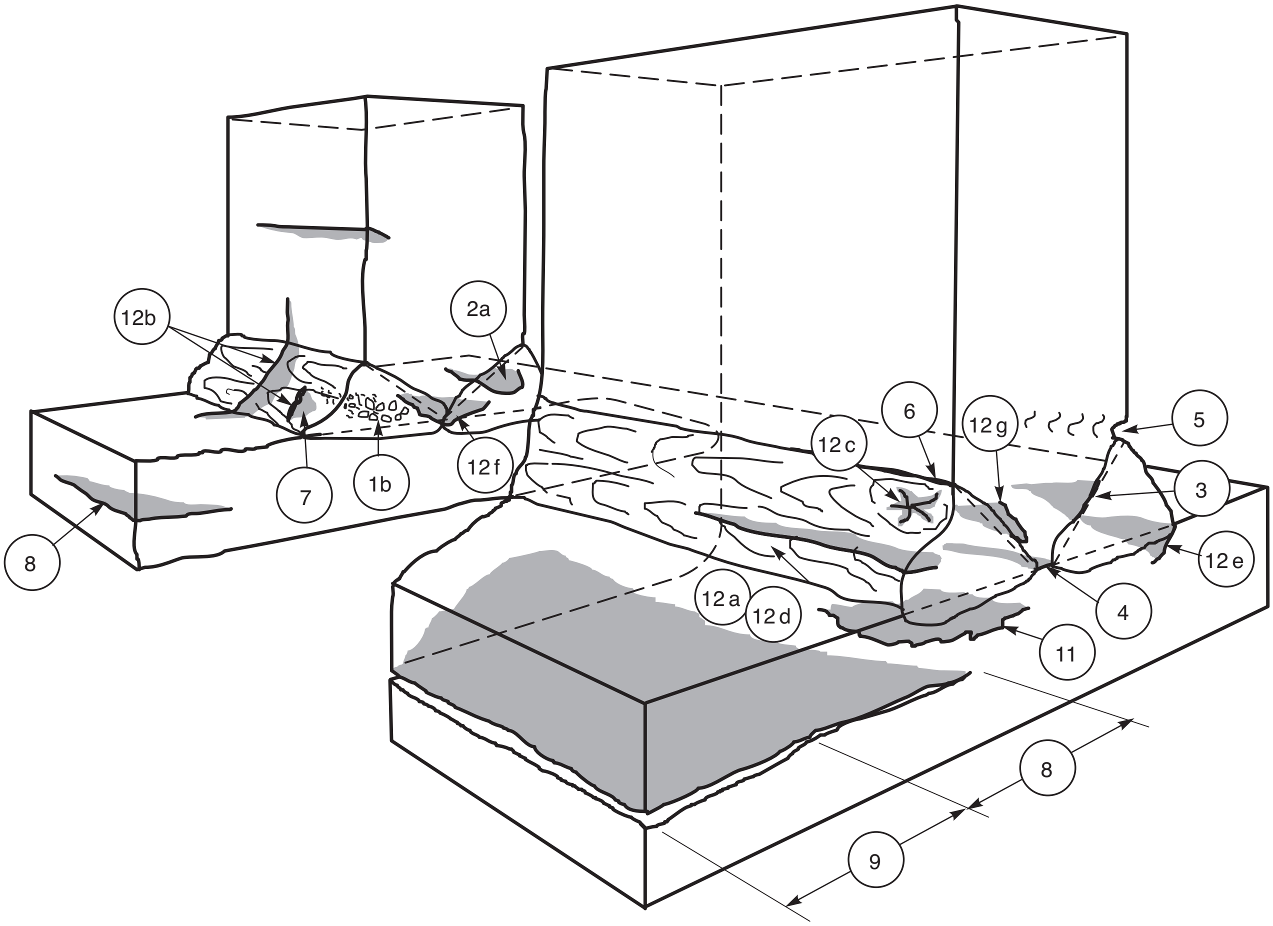

Figure L.3—Weld in T-Joint (see L2)

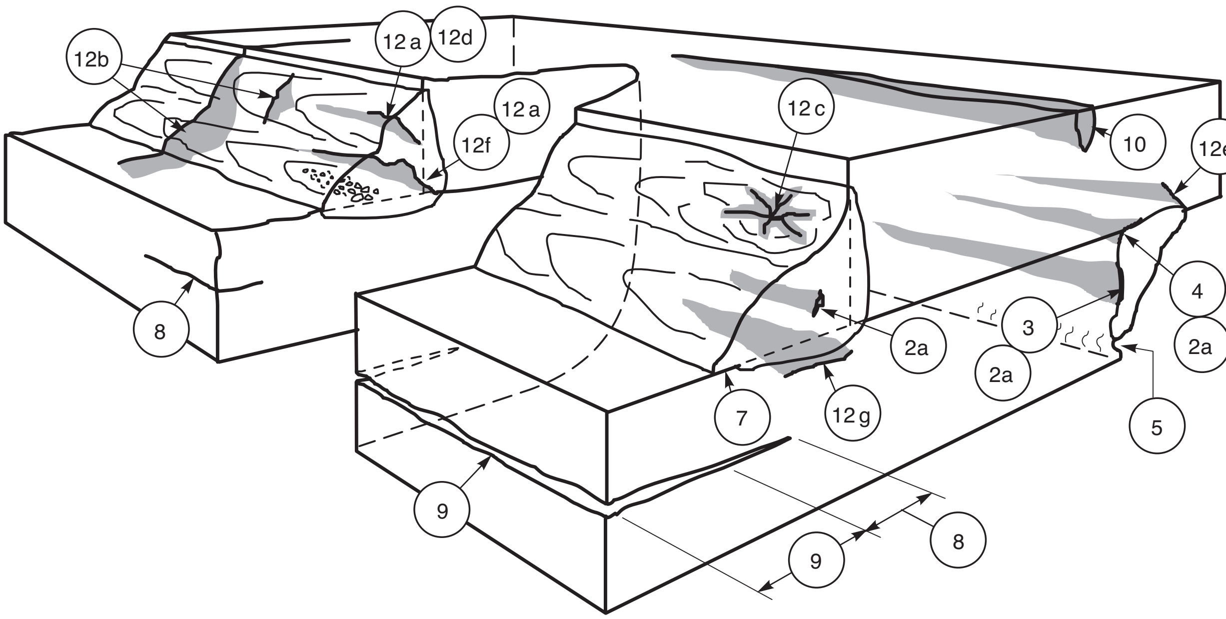

Figure L.4—Weld in Lap Joint (see L2)

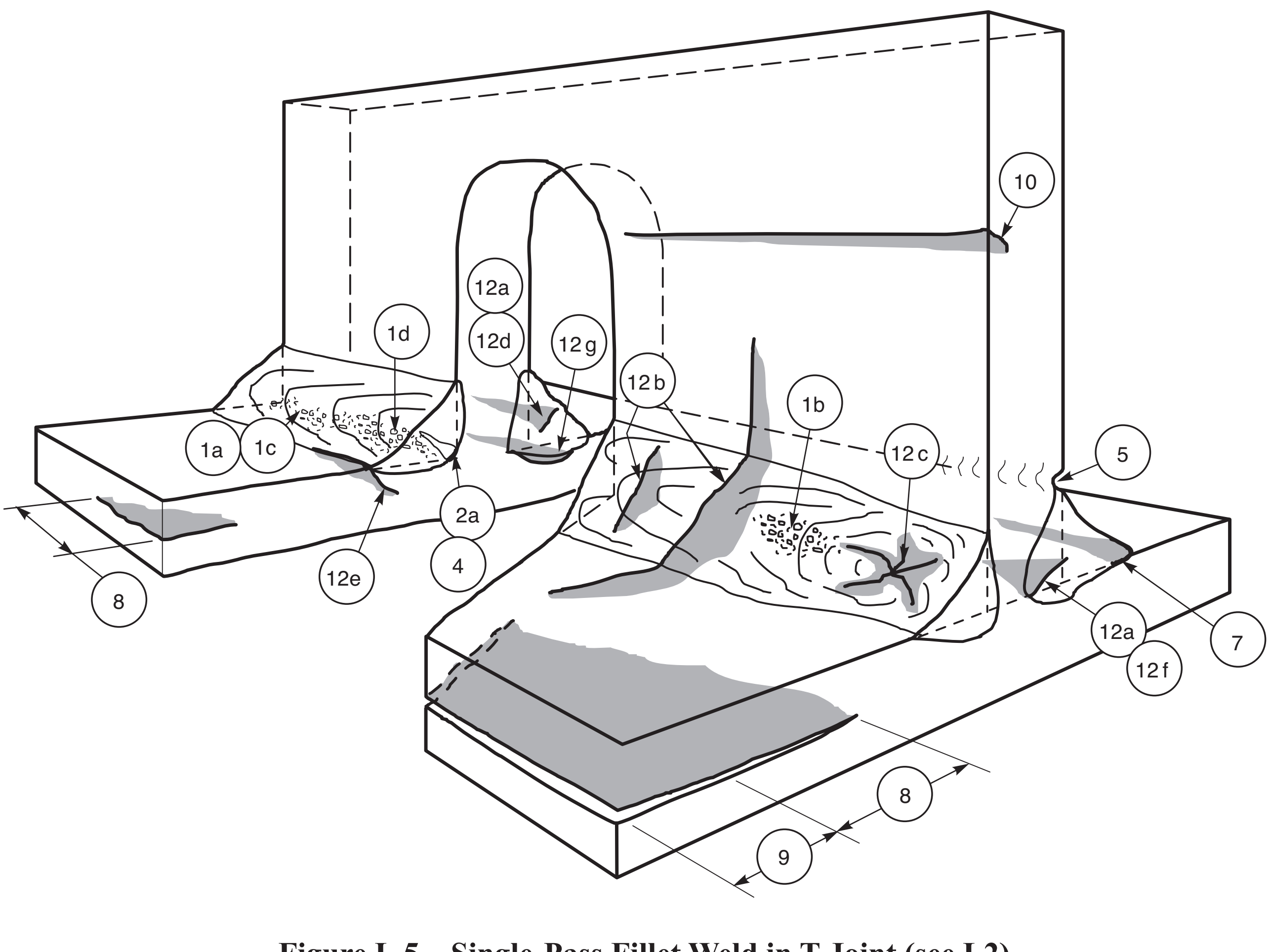

Figure L.5—Single-Pass Fillet Weld in T-Joint (see L2)

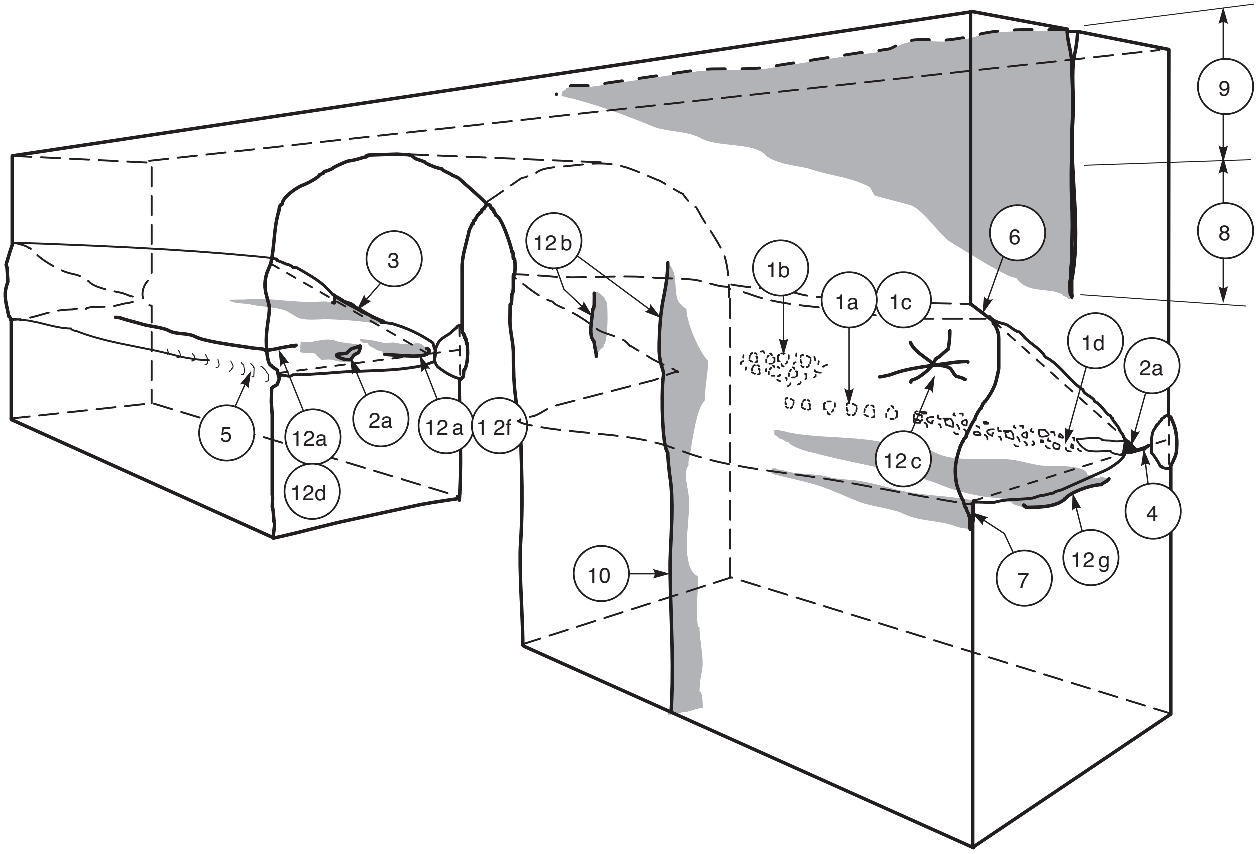

Figure L.6—Single-V-Groove Weld in Butt Joint (see L2)

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Annex M (Informative) Short Circuiting Transfer

These annexes are not considered part of the standard and are provided for informational purposes.

Short circuiting transfer is a type of metal transfer in GMAW is which melted material from a consumable electrode is deposited during repeated short circuits.

Short circuiting arc welding uses the lowest range of welding currents and electrodes diameters associated with GMAW. Typical current ranges for steel electrodes are shown in Table M.1. This type of transfer produces a small, fast freezing weld pool that is generally suited for the joining of thin sections, for out-of-position welding, and for the filling of large root openings. When weld heat input is extremely low, plate distortion is small. Metal is transferred from the electrode to the work only during a period when the electrode is in contact with the weld pool. There is no metal transfer across the arc gap.

The electrode contacts the molten weld pool at a steady rate in a range of 20 to over 200 times each second. The sequence of events in the transfer of metal and the corresponding current and voltage is shown in Figure M.1. As the wire touches the weld metal, the current increases. It would continue to increase if an arc did not form, as shown at E in Figure M.1. The rate of current increase shall be high enough to maintain a molten electrode tip until filler metal is transferred. Yet, it should not occur so fast that it causes spatter by disintegration of the transferring drop of filler metal. The rate of current increase is controlled by adjustment of the inductance in the power source. The value of inductance required depends on both the electrical resistance of the welding circuit and the temperature range of electrode melting. The open circuit voltage of the power source shall be low enough so that an arc cannot continue under the existing welding conditions. A portion of the energy for arc maintenance is provided by the inductive storage of energy during the period of short circuiting.

Table M.1
Typical Current Ranges for Short Circuiting Transfer Gas Metal Arc Welding of Steel (GMAW-S)

Welding Current, Amperes (Electrode Positive)					
Electrode Diameter		Flat and Horizontal Positions		Vertical and Overhead Positions	
in	mm	min.	max.	min.	max.
0.030	0.8	50	150	50	125
0.035	0.9	75	175	75	150
0.045	1.2	100	225	100	175

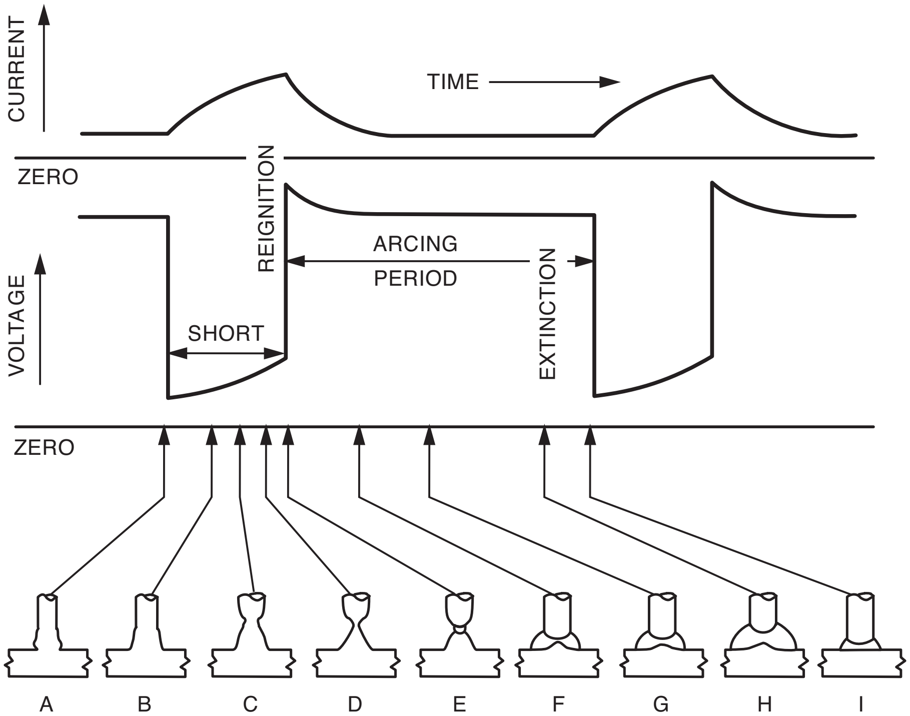

Figure M.1—Oscillograms and Sketches of Short Circuiting Transfer

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Annex N
Suggested Sample Welding Forms

This annex is not part of this standard but is included for informational purposes only.

This annex contains six forms that the Structural Welding Committee has approved for the recording of WPS qualification, welder qualification, welding operator qualification, and tack welder qualification data required by this code. Also included are laboratory report forms for recording the results of NDT of welds.

It is recommended that the qualification and NDT information required by this code be recorded on these forms or similar forms prepared by the user. Variations of these forms to suit the user's needs are allowable. These forms are available from AWS.

______________ (Manufacturer's name ______________

______________ and address) ______________

CERTIFICATION OF CONFORMANCE

Supplied to ________________________________ Date ______________

Purchase Order No. ______________ Quantity ______________ Project No. ______________

Reported to ________________________________

Process: SMAW ☐ GMAW ☐ SAW ☐ ESW ☐ FCAW ☐ EGW ☐

		AWS A5.____ and Classification	Trade Name
Material:	Electrode Designation	______________	______________
	Wire Designation	______________	______________
	Flux Designation	______________	______________
	Gas/Gas Mixture	______________	______________

This is to certify that the above noted material, as supplied under the above Purchase Order Number, is in conformance with the requirements of AWS A5._____–_____on________________,_______.
(day, month) (year)

The results of the required manufacturer's annual tests are shown on the attached Certified Material Test Report. Test results for this Certification shall include:

(a) Mechanical Tests: Tensile and Yield Strengths (MPa [ksi]), Elongation (in 50 mm [2 in], %), and CVN test energy (J [ft·lb] at test temperature).

(b) Chemical Analysis for C, Mn, Si, P, S, Ni, Cr, Mo, Cu, V, Al, Ti, or Zr, as require d by the applicable filler metal specification.

(c) Fillet Weld Test.

(d) Radiographic Results.

For applicable test requirements, see the appropriate AWS filler metal specification.

Signature________________________________ Date ______________ Title ______________

Form N-1

Form N-1—Certificate of Conformance to Requirements for Welding Electrodes

WELDING PROCEDURE SPECIFICATION (WPS)
PREQUALIFIED ☐ QUALIFIED BY TESTING ☐
or PROCEDURE QUALIFICATION RECORDS (PQR) Yes ☐
AASHTO/AWS D1.5 Qualification Type 7.12.1 ☐ – 7.12.2 ☐ – 7.12.4 ☐

Contractor/
Organization ____________________
Welding Process(es) ____________________
Type: Manual ☐ Semiautomatic ☐
Mechanized ☐ Automatic ☐
Tandem ☐ Parallel ☐

JOINT DESIGN USED
Single ☐ Double Weld ☐
Backing: Yes ☐ No ☐ Material ________
Root Opening ______ Root Face Dimension ________
Groove Angle __________ Radius (J–U) ________
Backgouging: Yes ☐ No ☐ Method ________
Root Treatment ____________________

BASE METALS
Material Spec. ____________________
Type or Grade ____________________
Thickness: Groove __________ Fillet ________
Diameter (Pipe) ____________________

FILLER METALS
AWS Specification ____________________
AWS Classification ____________________
Manufacturer Trade Name ____________________

SHIELDING
Flux ________ Mfg. Trade Name ____________
Electrode-Flux (Class) ____________________
Gas Composition ____________________
Flow Rate __________ Gas Cup Size ________

Identification ____________________
Revision _______ Date ________ By ________
Authorized by ____________ Date ________
Supporting PQR No.(s) ____________________

POSITION
Position of Groove __________ Fillet ________
Vertical Progression: Up ☐ Down ☐

ELECTRICAL CHARACTERISTICS
Transfer Mode (GMAW): Globular ☐ Spray ☐
Current: AC ☐ DCEP ☐ DCEN ☐ Pulsed ☐
Electrical Stick Out ____________________
Other ____________________

TECHNIQUE
Stringer or Weave Bead ____________________
Multi-pass or Single Pass (per side) ____________
Number of Electrodes ____________________
Electrode Spacing: Longitudinal ____________
Lateral ______________ Angle ________
Interpass Cleaning ____________________

PREHEAT
Preheat Temp., Min. ____________________
Interpass Temp., Min. ____________________
Interpass Temp., Max. ____________________

POSTWELD HEAT TREATMENT
Temp. ____________ Hold Time ________
Heating/Cooling Rate ____________________

HEAT INPUT
Calculated Heat Input Value: kJ/in ☐ kJ/mm ☐
Max. Heat Input ________ Min. Heat Input ________

WELDING PROCEDURE

Pass or Weld Layer(s)	Process	Filler Metals Diam.	Current Type & Polarity	Current Amps or Wire Feed Speed	Volts	Travel Speed	Joint Details

Form N-2

Form N-2—Sample Welding Procedure Specification

PROCEDURE QUALIFICATION RECORD

PQR NUMBER________________ *(Include PQR Number on All Supporting Documents)*

Welder's Name ______________________ ID________ Welding Test Date ________________________________

Process ________________ Position______________ Joint Detail: ☐ Fig. 7.1 ☐ Fig. 7.2 ☐ Fig. 7.3 ☐ Fig. 7.8

Electrode(s) Mfg. Designation_____________________

AWS Electrode Classification _____________________ Electrical Stick Out ________________________________

Flux Mfg. Designation ____________________________ AWS Flux Classification ___________________________

Postweld Heat Treatment: Temp.________________ Hold Time_______________ Heating/Cooling Rate _________

		Diam.	Current	WFS*	Voltage	Current and Polarity
Electrode	(1)	_________	_________	_________	_________	_________
	(2)	_________	_________	_________	_________	_________
	(3)	_________	_________	_________	_________	_________

Calculated Heat Input (see 7.12) ___________________

Shielding Gas _________ Dew Point _____________ Flow Rate _____________ Gas Cup Size __________

Travel Speed: Min. ___________ Max.____________

Base Metal Specification and Thickness_____________ Heat Number ___________________________________

Backing Metal Specification and Thickness __________ Heat Number ___________________________________

Base Metal Carbon Equivalent____

(Attach Copy of Certified Mill Test Report for Base and Backing Materials)

Preheat Temp.__________________________________ Interpass Temp. Min. __________ Max.___________

SPECIMEN	TEST RESULTS
All Weld Metal Tension (AWMT) ☐ ksi ☐ MPa	Tensile Strength_______________ Yield Strength _______________ Elongation in 50 mm [2 in] (%) _______________ Reduction in Area % _______________
Visual Inspection: ☐ Acceptable ☐ Unacceptable	**Macro Test: ☐ Acceptable ☐ Unacceptable
Side Bends	1. ____________ 2. ____________ 3. ____________ 4. ____________
Reduced Section Tension ☐ ksi ☐ MPa	Tension Strength 1. ____________ 2. ____________ Location of Break 1. ____________ 2. ____________
Charpy V-Notch Impact Toughness of Weld Metal SMAW, SAW, FCAW, GMAW—5 Req'd. ESW and EGW—8 Req'd.	(___________ , ___________ , ___________ , ___________ , _________) (___________ , ___________ , ___________) [a]Avg. ☐ ft·lbs, ☐ J ___________ @ ___________ ☐ °F ☐ [°C] [a]*Discard the highest and lowest values and average the 3 remaining.*
**Chemical Composition of Deposited Weld Metal When Required by Contract Documents*	C________ Mn______ Si_______ P _______ S________ Ni _______ Cr ______ Mo ______ V _______ Cu_______
Radiographic Test: ☐ Acceptable ☐ Unacceptable	Remarks: ______________________________________
Fillet Weld Soundness Macroetch	Maximum Size Single Pass: __________ 1.__________ 2.__________ 3.__________ Minimum Size Multiple Pass: __________ 1.__________ 2.__________ 3.__________

We, the undersigned, certify that the above described WPQR/FWS has been qualified in accordance with Clause 7 of the AASHTO/AWS D1.5M/D1.5, (__________) *Bridge Welding Code*.
(year)

State/3rd Party Witness __________________________ Mfr./Contractor __________________________________

Date ____

Authorized By __________________________________

Agency Results Reviewed________________________

Date ____ Date ____

*Optional **Optional for CJP

Form N-3

Form N-3—Procedure Qualification Record (PQR) for Qualification, Pretest, and Verification Results

PROCEDURE QUALIFICATION RECORD WORKSHEET
PQR NUMBER________________

Welder's Name______________________ ID________ Welding Test Date ______________________________

Process _________________ Position______________ Joint Detail: ☐ Fig. 7.1 ☐ Fig. 7.2 ☐ Fig. 7.3 ☐ Fig. 7.8

Electrode(s) Mfg. Designation______________________

AWS Electrode Classification ______________________ Electrical Stick Out ______________________________

Flux Mfg. Designation ___________________________ AWS Flux Classification ___________________________

Postweld Heat Treatment: Temp.______________Hold Time________________ Heating/Cooling Rate _________

		Diam.	Current	WFS*	Voltage	Current and Polarity
Electrode	(1)	________	________	________	________	________
	(2)	________	________	________	________	________
	(3)	________	________	________	________	________

Shielding Gas _________ Dew Point ____________ Flow Rate _____________ Gas Cup Size __________

Travel Speed: Min.____________Max.______________

Base Metal Specification and Thickness_____________ Heat Number ___________________________________

Backing Metal Specification and Thickness __________ Heat Number ___________________________________

Preheat Temp.________________________________ Interpass Temp. Min. __________ Max.___________

Pass Number	Layer	Process	FILLER METAL	CURRENT						TEMPERATURE	
			Diam.	Type & Polarity	Wire Feed Speed	Amp	Volts	Travel Speed	Stick Out	Preheat	Interpass

*Optional

Page________of ________

For multiple electrodes, list each electrode on separate line. For parallel electrodes, show "2 @________" under number and diameter. Measure preheat and interpass at mid length of plate approximately 25 mm [1 in] from the weld center line.

State/3rd Party Witness _________________________ Mfr./Contractor ________________________________

Date ____

Form N-4

Form N-4—Procedure Qualification Record (PQR) Worksheet

WELDER AND WELDING OPERATOR QUALIFICATION RECORD

Welder or welding operator's name__________ Identification no. __________
Welding process______ Manual______ Semiautomatic______ Mechanized______
Position__________
(Flat, horizontal, overhead or vertical—if vertical, state whether upward or downward)
In conformance with WPS no. __________
Material specification __________

FILLER METAL

Specification no.______ Classification______ F no. ______
Describe filler metal (if not covered by AWS specification) __________
Is backing used? __________
Filler metal diameter and trade name ______ Flux for SAW or gas for GMAW or FCAW-G ______

VISUAL INSPECTION (8.26.1)

Appearance______ Undercut______ Piping porosity ______

Guided Bend Test Results

Type	Result	Type	Result

Test conducted by ______ Laboratory test no. ______
per ______ Test date______

Fillet Test Results

Appearance______ Fillet size ______
Fracture test root penetration ______ Macroetch ______
(Describe the location, nature, and size or any crack or tearing of the specimen.)
Test conducted by ______ Laboratory test no. ______
per ______ Test date______

RADIOGRAPHIC TEST RESULTS

Film Identification	Results	Remarks	Film Identification	Results	Remarks

Test witnessed by ______ Test no.______
per ______

We, the undersigned, certify that the statements in this record are correct and that the welds were prepared and tested in conformance with the requirements of AASHTO/AWS D1.5M/D1.5, (______) *Bridge Welding Code*.
(year)

Manufacturer or Contractor ______
Authorized By______
Date______

Form N-5

Form N-5—Welder and Welding Operator Qualification Record

REPORT OF RADIOGRAPHIC EXAMINATION OF WELDS

Project ______________________________

Quality requirements—Section no. ______________________________

Reported to ______________________________

WELD LOCATION AND IDENTIFICATION SKETCH

Technique

Source ______________________________

Film to source ______________________________

Exposure time ______________________________

Screens ______________________________

Film Type ______________________________

(Describe length, width, and thickness of all joints radiographed)

Date	Weld Identification	Area	Interpretation		Repairs		Remarks
			Accept	Reject	Accept	Reject	

We, the undersigned, certify that the statements in this record are correct and that the welds were prepared and tested in conformance with the requirements of AASHTO/AWS D1.5M/D1.5, (__________) *Bridge Welding Code*.
(year)

Radiographer(s) ______________________________

Interpreter ______________________________

Test Date ______________________________

Manufacturer or Contractor ______________________________

Authorized By ______________________________

Date ______________________________

Form N-6—Report of Radiographic Examination of Welds

REPORT OF MAGNETIC PARTICLE EXAMINATION OF WELDS

Project ____________________

Quality requirements—Section no. ____________________

Reported to ____________________

WELD LOCATION AND IDENTIFICATION SKETCH

Date	Weld Identification	Area	Interpretation		Repairs		Remarks
			Accept	Reject	Accept	Reject	

We, the undersigned, certify that the statements in this record are correct and that the welds were prepared and tested in conformance with the requirements of AASHTO/AWS D1.5M/D1.5, (__________) *Bridge Welding Code.*
(year)

Inspector ____________________ Manufacturer or Contractor ____________________

Test Date ____________________ Authorized By ____________________

Date ____________________

☐ Dry ☐ Wet ☐ Residual ☐ Continuous

☐ AC ☐ DC ☐ Half-wave

Form N-7

Form N-7—Report of Magnetic Particle Examination of Welds

ESW-NG PROCEDURE QUALIFICATION RECORD	Document No.: ______ Issue Date: ______ Rev. ______ Page No.: ______ Prepared by: ______ Approved: ______

Date:	WPS No.:	PQR NO.:

Specification/Code:	Material Specification:
Welding Process: ESW-NG	Welding/Machine: MECHANIZED—AUTOMATIC
Welding Operator:	Welding Operator ID:
Material Thickness:	Thickness Qualified:
Filler Metal Specification:	Filler Metal Classification:
Filler Metal Manufacturer:	Trade Name:
Test Plate Heat Number:	Test Plate Producer:

Single/Multiple Pass: SINGLE	Preheat Temperature: NO PREHEAT REQUIREMENT
Welding Current:	Postheat Requirements: NONE
Polarity:	Interpass Temperature: N/A
Root Treatment:	

Preweld Flux Dump:	Flux Type:
Initial Flux Feed:	Current:
In-Weld Flux Feed:	Voltage:
Vertical Rate of Rise (in weld):	Wire Feed Rate:
Electrode Diameter:	Number of Electrodes:
Sealing Material for Slag Run-Out:	

Form N-8

Form N-8—ESW-NG Procedure Qualification Record

COOLING SHOES			WELD JOINT DETAIL		CONSUMABLE GUIDE	
Shoe Material:			Welding Position:	VERTICAL	Guide Material:	
A:	B:	C:	Progression:	UPWARD	A:	B:

NDE TESTING RESULTS (ACCEPTANCE PER AWS D1.5, 8.26.2.1 [for RT], 8.26.3.1—Table 8.4 [for UT])	
RT Testing Performed by:	Technician:
Test Report Number:	Results:
UT Testing Performed by:	Technician:
Test Report Number:	Results:

MACROETCH/VISUAL INSPECTION RESULTS (ACCEPTANCE PER AWS D1.5, 7.19.2.1, 8.26.1)		
Performed by:	No. of Samples:	Cracks:
Technician:	Complete Fusion:	Undercut:
Test Report Number:	Underfill:	Porosity:

Form N-8

Form N-8 (Continued)—ESW-NG Procedure Qualification Record

MECHANICAL TESTING RESULTS		
CVN TESTS (Rpt #:)	Prepared Per: AWS D1.5, Figs. 7.13 and 7.15	Acceptance Per: AWS D1.5, Table 7.3
	WELD METAL	
	ft·lb	
	ft·lb	
	ft·lb	
	ft·lb	
	ft·lb	
	ft·lb	
	ft·lb	
	ft·lb	
	Test Temperature:	
	Average: ft·lb	
	Req'd.: 20 ft·lb @ –20 °C [27 J @ 0 °F]	
	Result:	
All Weld Metal Tensile (Rpt #:)	Prepared Per: AWS D1.5, Fig. 7.9	Acceptance Per: AWS D1.5, Table 7.3

PARAMETER	TEST VALUE	REQUIREMENT	TEST RESULT
Tensile Strength:		70 ksi, min.	
Yield Strength:		50 ksi, min.	
Elongation:		22%, min.	

Form N-8

Form N-8 (Continued)—ESW-NG Procedure Qualification Record

Reduced Sect. Tensile (Rpt #:)		Prepared Per: AWS D1.5, Fig. 7.10		Acceptance Per: AWS D1.5, Table 7.3
SAMPLE REF.	**SAMPLE SIZE**	**TEST VALUE**	**REQUIREMENT**	**TEST RESULT**

SIDE BEND TEST (Rpt #:)	Prepared Per: AWS D1.5, Fig. 7.11	Acceptance Per: AWS D1.5, 7.19.1
Test Ref.: Result:	Test Ref.: Result:	Test Ref.: Result:
Test Ref.: Result:	Test Ref.: Result:	Test Ref.: Result:

Authorized by:	Witnessed by:	Approval:

Form N-8

Form N-8 (Continued)—ESW-NG Procedure Qualification Record

ESW-NG WELDING PROCEDURE SPECIFICATION	Document No.: ____________ Issue Date: ____________ Rev. ______ Page No.: ____________ Prepared by: ____________ Approved: ____________

Date:	WPS No.:	
Specification/Code:	Material Specification:	
Specification Process: ESW-NG	Welding/Machine: MECHANIZED—AUTOMATIC	
Material Thickness:	Weld Thickness (for Transition Joints):	
Filler Metal Specification:	Filler Metal Classification:	
Filler Metal Manufacturer:	Trade Name:	
Shielding Gas: N/A	Flow Rate: N/A	Dew Point: N/A

Single/Multiple Pass: SINGLE	Preheat Temperature: NO PREHEAT REQUIREMENT
Welding Current:	Postheat Requirements: NONE
Polarity:	Interpass Temperature: N/A
Root Treatment:	

Preweld Flux Dump:	Flux Type:
Initial Flux Feed:	Current:
In-Weld Flux Feed:	Voltage:
Vertical Rate of Rise (in weld):	Wire Feed Rate:
Electrode Diameter:	Number of Electrodes:
Sealing Material for Slag Run-Out:	

Form N-9

Form N-9—ESW-NG Welding Procedure Specification

<table>
<tr><th colspan="3">COOLING SHOES</th><th colspan="2">WELD JOINT DETAIL</th><th colspan="2">CONSUMABLE GUIDE</th></tr>
<tr><td colspan="3"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="3">Shoe Material:</td><td>Welding Position:</td><td>VERTICAL</td><td colspan="2">Guide Material:</td></tr>
<tr><td>A:</td><td>B:</td><td>C:</td><td>Progression:</td><td>UPWARD</td><td>A:</td><td>B:</td></tr>
</table>

Authorized by:	Approval:

Form N-9

Form N-9 (Continued)—ESW-NG Welding Procedure Specification

Annex O (Informative) Guide for Use of Electroslag Welding— Narrow Gap (ESW-NG)

This annex is not part of this standard but is included for informational purposes only.

O1. General

O1.1 Scope. This nonmandatory annex is a Recommended Practices Guide that may be used when ESW-NG is performed in accordance with the mandatory provisions of this code. The material contained in this guide is intended to explain the provisions of this code and provide suggested practices that are based on past experience, research, or good judgment. Parts or all of this annex may be used when the welding process is qualified in accordance with this annex.

O1.2 Background. In 1977, the Federal Highway Administration (FHWA) placed a moratorium on the use of ESW for the construction of bridge members carrying applied tension in response to a major brittle fracture in an electroslag-welded bridge girder on I-79 near Pittsburgh, PA. The electroslag weld that failed had been extensively and improperly repaired during fabrication. Nondestructive tests required by the specifications failed to reject critical defects that remained in the weld. Subsequent investigations of electroslag welds in other bridges also revealed significant weld fusion defects and some cracking. Although the moratorium only prohibited the electroslag process for welds subject to applied tensile stress, it effectively stopped all ESW of bridge members.

Recognizing the high efficiency of ESW for bridge construction, the FHWA sponsored research and development to improve the soundness and reliability of welds made by that process. The goals were to improve the fracture resistance and fatigue performance while ensuring consistent quality and repeatable parameters for electroslag bridge welds subject to dynamic loading conditions.

Welding research and fatigue tests demonstrated that the procedure described in this specification as narrow-gap improved ESW (ESW-NG) produces sound welds with acceptable toughness in the weld metal and HAZ. Fullscale bridge members with electroslag groove welds in flange butt joints survived more than 10 million cycles of stress at typical bridge design stress ranges.

O2. Background Documents

(1) *FHWA Report No. FHWA/RD-87/026, Improved Fracture Toughness and Fatigue Characteristics of Electroslag Welds*—1987.

(2) *FHWA Report No. FHWA-SA-96-053, Technical Information Guide for Narrow-Gap Improved Electroslag Welding.*

(3) *FHWA Report No. FHWA SA-96-052, Process Operational Guide for Narrow-Gap Improved Electroslag Welding.*

(4) *FHWA Report No. FHWA-SA-96-051, Training Manual for Narrow-Gap Improved Electroslag Welding for Bridges.*

These documents and reports are available from the FHWA Office of Bridge Technology, <http://www.fhwa.dot.gov/bridge/>.

O3. Definitions

electroslag welding—narrow gap (ESW-NG). A variation of electroslag welding characterized by a narrow gap (root opening) of approximately 20 mm [3/4 in] and the use of a metal cored electrode that is fed through a special winged consumable electrode guide that aids in distributing the thermal energy across the weld joint.

O4. Process Description

ESW is a welding process that produces coalescence of metals with molten slag that melts the filler metal and the surfaces of the workpieces. The weld pool is shielded by this slag which moves along the full cross section of the joint as welding progresses. The process is initiated by an arc that heats the slag. The arc is then extinguished by the conductive slag, which is kept molten by its resistance to electric current passing between the electrode and the workpieces.

ESW-NG is a variation of electroslag welding characterized by a narrow gap (root opening) of approximately 20 mm [3/4 in]. Compared to conventional electroslag welding, the ESW-NG process is characterized by: (1) improved CVN toughness of the weld metal and HAZ, (2) higher fatigue resistance, and (3) increased productivity. ESW-NG utilizes a metal cored electrode and winged consumable electrode guides.

O5. Equipment

O5.1 Welding Power Source. A DC power source is recommended. The power source should be capable of delivering the required current and voltage that, for single electrode applications, ranges from 600 A to 1000 A and 29 V to 37 V, at a 100% duty cycle. The output should be constant voltage (CV). A variety of types of power supplies may be used, but some of the modern electronic controls on power supplies may result in inadvertent shutdowns. Such shutdowns are typically associated with welding machines that limit the maximum peak current to protect the output rectifiers. Thus, the 100% duty cycle current and voltage output rating as well as the peak amperage capability are important.

O5.2 Wire (Electrode) Feeder. The wire feeder should have wire feed speed controls for use with the ESW-NG process.

O5.3 Automatic Flux Feeder. Code requirements for automatic flux feeders are contained in 6.22.10. The code requires the use of an automatic flux feeder to supply a regulated, continuous flow of new flux after the process has stabilized (e.g., after the weld leaves the sump). The rate and consistency of flux additions are critical as they affect the thermal balance and characteristics of the ESW-NG process. Unregulated flux additions may cause weld defects.

Q5.4 Current and Voltage Monitors. Code requirements for current and voltage monitors are contained in 6.22.10. A device for monitoring current and voltage is required by 6.22.10. It is intended that this device be used for informational purposes and is not intended as a basis for acceptance or rejection of the weld. Slag pool depth is not measured directly. Instead, as slag depth decreases, fluctuations or spiking will appear on the recorder trace and the flux feed rate should be increased to restore proper slag pool and amperage trace conditions. Welding for several minutes with no fluctuation in the amperage trace may indicate development of an excessively deep slag pool. To avoid weld defects caused by excessive slag pool depth, the flux feed rate should be reduced or stopped until slight fluctuations appear in the amperage trace, and then the automatic flux addition can resume.

O5.5 Consumable Guide. Code requirements for consumable guides are contained in 6.19.2 and 6.22.2.

O5.5.1 Guide Configuration. Recommended guide configurations are as shown in Table O.1.

O5.5.2 Composition. Consumable guides may be manufactured from low-carbon cold-rolled steel bar and/or tubing, in accordance with Table H.2. The consumable guide chemical composition requirements are intended to reduce susceptibility to solidification cracking. In ESW-NG, the base metal composition, having low resistance to solidification cracking, contributes about 40% of the weld admixture. As a result, the filler metal composition must counter the deleterious effects of the base metal. Many of the materials listed under SAE 1006, ASTM A1008/A1008M, A424, and A1011/A1011M can be ordered with restrictions on carbon, phosphorus, and sulfur to produce consumable guides satisfying the requirements of Annex H.

O5.5.3 Guide Condition and Storage. The guides typically do not have any type of protective coatings, and therefore need to be stored and handled carefully to prevent contamination and rusting of the guides. Rust developing on the guides may be the biggest problem because the materials are typically very clean and may flash rust quickly if not packaged, stored, and handled carefully.

Packaging and control of guides should be adequate to prevent rusting during shipping, storage, and use. After opening containers holding multiple guides without individual protection, guides not initially used need to be placed in moisture resistant-barrier packaging, a saleable container, a holding oven, or other type of controlled environment to prevent rusting from atmospheric exposure. If preservatives are used, they must be removed or otherwise dissipate before use so no hydrocarbons or other detrimental elements enter the weld deposit.

Guides exhibiting light surface rust or other contaminants that can be removed easily before use should be acceptable. The use of guides with readily visible rust or other contaminants that cannot be removed is prohibited.

O5.5.4 Guide Passage. Code requirements for the maximum opening for electrode passage are contained in 6.22.3. Limits on wire passage opening are intended to allow proper current transfer.

O5.5.5 Placement. Code requirements for guide placement are contained in 6.22.2. The required distance from the edge of the guide to the cooling shoe is intended to prevent arcing to the shoe while still allowing good fusion near the face of the weld. It is desirable to use a guide support system that permits the guide to be adjusted in all three orthogonal directions.

O5.6 Retaining Shoes. Code provisions governing retaining shoes are contained in 6.22.5.

O5.6.1 Purpose. Among the many functions of the shoes is withdrawing heat from the molten zone. This is important because the low-melting-point slag must be able to solidify to form a boundary layer on the shoe walls to protect the shoes from bonding with the molten steel. It is important that the shoes provide adequate cooling to produce:

(1) a thin solid slag buffer layer between the shoe and molten steel, and

(2) tough microstructure to ensure acceptable CVN toughness of the weld metal and the HAZ.

O5.6.2 Design. Shoe design must provide efficient transfer of heat from the molten pool to the water cooling system. Shoes should be at least 100 mm [4 in] wide in order to provide sufficient contact and cooling on the plate adjacent to the weld groove. There is a diminishing return to greater shoe width relative to cost, increased cooling, ease of handling, and practical design for manufacturing. For the same reasons, shoe length is typically held between 300 mm to 450 mm [12 in to 18 in]. A very effective water passage design regarding both fabrication and heat extraction is to drill intersecting 10 mm [3/8 in] diameter holes in a solid 25 mm [1 in] thick copper block.

The weld reinforcement groove on the face of the cooling shoe should be 1.9 mm to 2.1 mm [0.075 in to 0.083 in] deep and 24 mm to 26 mm [15/16 in to 1-1/16 in] wide with a 2 mm to 3 mm radius [0.08 in to 0.12 in] on each edge. The depth of the reinforcement groove determines the volume of slag that solidifies between the weld face and cooling shoe as well as the volume and shape of the weld reinforcement that may require removal by grinding or machining. The overall weld reinforcement groove design and cooling shoe fitup on the weld is also essential to prevent weld undercut.

O5.6.3 Composition. The recommended shoe material is commercially pure copper, including such varieties as tough pitch copper, OFHC copper, and phosphorusdeoxidized copper. Copper alloys such as copper-nickel alloys or various brasses and bronzes would not be acceptable because of the relatively low thermal conductivity of these alloys (compared to pure copper).

O5.6.4 Water Cooling. Water cooling of the retaining shoes is essential to maintain steady state cooling conditions for the ESW-NG process. However, there are several variables that affect the heat transfer rate of the cooling shoes. These include water flow rate and water temperature rise during welding. As discussed above, it is recommended that the shoes on each side of the weld be connected in series. If water flow and design conditions are correct, the copper in the cooling shoes should be warm to the touch but not hot; monitoring the shoe metal temperature is not necessary. The cooling water should be turned on only immediately before welding begins as this will minimize the possibility of condensation of moisture on the retaining shoes.

Temperature rise of water depends on whether the type of cooling system is a recirculation system or water drawn from the tap. If the water cooling is recycled through a water recirculator, the water temperature will rise as the weld progresses, and so the start of the weld would be cooled with cooler water than the end of the weld. This could cause differences in microstructure and mechanical properties between the start and end portions of the weld.

When water is drawn from an open tap and subsequently disposed down a drain, the only variable to note is the incoming and exiting water temperatures. During the summer in some locations, the tap water temperature can exceed 27°C [80°F]. On the other hand, the tap water temperature in a cold climate may drop below 10°C [50°F]. During warm humid weather, cool tap water could cause condensation on shoe faces before welding begins. Care should be taken to prevent condensation caused by cooling the shoes below the atmospheric dew point in humid conditions (see 6.17.5).

Water fittings that have directional flow restriction may create problems because of the high potential for malfunction or improper installation that could prevent water flow. Trapped water in the cooling shoes can lead to very dangerous steam pressures. The welding operator should ensure that water is flowing prior to starting and during any welding, in order to protect the equipment and personnel in the area.

A common retaining shoe configuration on a weld assembly uses two cooling shoes stacked and connected in series for each side of the weld joint. Typically the weld will have cooled enough for the shoe to be removed two or three minutes after the slag pool advances onto the next shoe. Required flow rate and temperature rise is intended to be interpreted over the length of the weld, not on an instantaneous basis. The prescribed temperature rise indicates effective cooling, but deviations at the beginning or end of the weld should not be cause for concern.

O5.7 Controls for Water Cooling. Requirements for controls are contained in 6.22.5. Shoes along one side of the weld may be plumbed in series, but each side should be plumbed separately; the water from the shoes on one side should not be cycled directly into the copper shoes on the other side of the weld joint before the water is cooled. The cooling shoes should remain in place with water flowing for a minimum of two minutes after the slag pool advances to the next shoe or upon completion of the weld.

O5.8 Insulators. Requirements for insulators are contained in 6.21.

O5.8.1 Purpose. The insulators are positioned to prevent the magnetic field produced by welding current from pulling the consumable guide into contact with the base metal.

O5.8.2 Composition. The insulator composition is important because insulators are melted and mixed in the slag pool. Vitreous aluminosilicate fiber refractory material is recommended for insulators.

O5.8.3 Spacing. Insulators are typically placed 150 mm to 200 mm [6 in to 8 in] apart along the length of the weld joint. A closer spacing of insulators is not advisable because insulators affect the composition of the molten slag pool.

O5.8.4 Protection and Storage. The melting of the insulator into the slag pool can provide a possible source for introducing hydrogen or other contaminants into the weld pool. For this reason, after the insulator material has been removed from its original package, it must be protected and stored in a dry environment to prevent contamination or moisture pickup. Storage in a flux oven or baking is not required and may not be advisable as binders used in the fiber structure may be damaged by baking, which may reduce resilience under compression that effectively wedges the consumable guide in the weld groove.

O6. Electrodes and Flux

O6.1 Electrodes. Requirements for electrodes are contained in 6.22.6, Annex H, and Table 7.3. Only metal cored electrodes are permitted for use with ESW-NG under this code. Using tubular electrodes increases the welding speed and decreases the heat input because of the greater electrical resistance associated with tubular versus solid electrodes.

O6.1.1 Basic Composition. The electrode chemical composition is designed to provide weld metal with the following characteristics: (1) satisfactory CVN toughness, (2) resistance to solidification cracking, (3) resistance to hydrogen-assisted cracking, and (4) weathering resistance to match Grade 345W [50W] base metal. Annex H limits carbon to provide both toughness and resistance to cracking.

O6.1.2 Role of Alloys

(1) Manganese (Mn) is a strengthener that promotes the formation of tough acicular ferrite. Mn combines with the sulphur in the molten pool and forms MnS.

(2) Nickel (Ni) is added to the low-carbon manganese steel filler metal to achieve a Ni content of approximately 1.4% to 1.6%, depending on the dilution from the base metal and guide. Ni in the weld metal above 1% has the beneficial effects of not only enhancing CVN toughness, but also providing weathering resistance required for grade 345W weld

metal. The disadvantages of excessive weld metal Ni content are increased susceptibility to hydrogenassisted cracking and solidification cracking.

(3) Molybdenum (Mo) is added to minimize the amount of grain boundary ferrite and to promote a finer microstructure. Because Mo is a powerful strengthener, only limited amounts of Mo are added to achieve a weld content of approximately 0.2%.

(4) Titanium (Ti) is a microalloying addition to promote the maximum amount of acicular ferrite for toughness. Ti can reduce the susceptibility to solidification cracking. The beneficial toughening effect of titanium is optimum when the Ti content is approximately 0.01% in the weld metal. Excessive Ti beyond the limits of Annex H can cause a decrease in CVN toughness.

O6.1.3 Electrode Packaging and Storage. Requirements for electrode packaging and storage are contained in 6.19.1.

O6.2 Flux. Requirements for flux composition, packaging, and storage are contained in 6.20. Neutral flux is specified so that the slag and weld metal chemical composition does not change along the full length of the weld.

O7. Sumps and Run-off Tabs

O7.1 Sumps. Sumps, suggested sump dimensions, and methods of attachment are illustrated in Figure O.3. Provisions for sumps are contained in 5.12.2, 5.12.3, 6.22.4, and 6.22.9. The depth of the sump is important because it has to be long enough to allow the arc to stabilize and to achieve full fusion when the weld metal reaches the base metal. During the final moments of the run-on phase, the slag pool should be stabilized and the proper amperage and voltage should be maintained as the slag pool leaves the starting sump and enters the joint.

O7.2 Run-off Tabs. Run-off tabs are illustrated in Figure O.3. Provisions for run-off tabs are contained in 5.12.2 and 5.12.3. Weld tabs should be long enough so that any weld crater cavity is outside the length of the final weld. Typically this will require weld tabs to be 50 mm [2 in] or the thickness of the piece being welded, whichever is greater.

O8. Base Metals

O8.1 Permitted Base Metals. Code requirements for permitted base metals are contained in 1.2, Table 6.1, and 6.18.3. ESW-NG is not permitted to be used on quenched and tempered steels (Q&T), thermo-mechanical control processed (TMCP) steels, nor on steels that have a minimum specified yield strength that is greater than 345 MPa [50 ksi].

O8.2 Base Metal Condition. Code requirements for base metal condition are contained in 6.22.1.

O9. Joint Design

Code requirements for joint design are contained in 6.18. The root opening has a direct effect on a variety of welding variables and on the resultant weld metal and heat-affected zone properties. For a given wire feed speed, a joint with a narrower root opening will result in a faster vertical travel speed, less heat input, and faster cooling rates. Wider root openings will have the opposite effects. The direction of growth of the grains of weld metal will be affected by travel speed, and will in turn affect weld metal toughness. For these reasons, the code prescribes the root opening for ESW-NG.

O10. Assembly and Alignment

O10.3.1 Misalignment. No special alignment beyond the standard fabrication tolerances are applied to joints to be welded with ESW-NG. However, the root opening must be maintained within tolerances, and the cooling shoes must maintain close contact in order to contain the molten weld pool and slag.

O10.3.2 Strongbacks. Code provisions for strongbacks used to support retaining shoes are covered in 6.22.7. Strongbacks are not permitted to be attached to the base metal by welding as a weld imperfection may be left behind after the strongback is removed. When no other means of attachment is possible, the Engineer can approve alternate procedures that permit attachment of strongbacks by welds made under controlled conditions. The procedures should require the area of the attaching weld to be finished flush and inspected.

O11. Application Restrictions

ESW applications are described 6.18.3. The use of ESW for fracture-critical or Zone III applications is prohibited because the research that led to the lifting of the FHWA moratorium did not investigate the performance of ESW for fracture critical members and the Charpy Impact properties were not adequate for Zone III requirements.

O12. Process Variables

O12.1 Background. The production welding restrictions in the code are intended to provide adequate HAZ CVN toughness without depending on CVN testing of the HAZ. Based on tests in the FWHA-sponsored research, the target value provides HAZ toughness matching ASTM A709 non-fracture-critical base metal requirements for Grades 345 [50] and 345W [50W]. While the permissible ranges provide a confident expectation of similar HAZ toughness, the requirements of this clause may be adjusted as the ESW-NG process is further refined and more production experience is gained.

O12.2 General Operating Conditions. Code requirements for WPS variables are included in 6.18.2, 7.14.2, and Table 7.8. Suggested sample welding forms are contained in Annex N. Table O.2 provides welding conditions that have been used successfully in research, and may be used as an aid in developing welding procedures. Differences in equipment, flux chemical composition, weld groove spacing, electrode sheath thickness and cross-sectional configuration, and area of the consumable guide will influence the actual operating parameters. If the welding application is for a thickness transition joint as shown in Figure 4.7, the conditions selected should be for the thinner plate, with a set of weld cooling shoes designed to fit the 2.5:1 chamfer.

O12.3 Welding Voltage. Voltage requirements are specified in 6.22.8.1 and Table 6.7. Voltage in the ESW-NG process is an extremely important variable. It affects the stability of the process and is the primary variable that determines the depth of fusion and weld width. Depth of fusion must be somewhat greater in the center of the weld than at the edges to assure complete fusion at the outside edges, where the chilling effect of the water-cooled shoes must be overcome.

An increase in voltage increases weld width, increases the form factor, and thereby improves cracking resistance.

The voltage must be maintained within limits to assure stable operation of the process. If the voltage is low, short circuiting or arcing to the weld pool will occur. Excessive voltage may produce an unstable weld pool.

O12.4 Wire Feed Speed. Wire feed speed requirements are specified in 6.22.8.3. Wire feed speed rather than current is an essential variable for ESW because variability in the sheath thickness and cross-sectional configuration of cored electrodes will affect the amperage reading. The variability in slag pool depth and electrode sheath thickness makes it impossible to control current directly, and wire feed speed must be controlled instead.

Because ESW is a single-pass vertical welding process, the electrode wire feed speed controls the welding travel speed. Even though higher wire feed speeds produce higher amperage, the relationship is not linear. As the electrode speed increases, the resulting amperage increase is proportionately less. Maintaining a constant high welding travel speed and minimizing welding heat input is necessary to achieve the required impact toughness properties in the HAZ.

O12.5 Amperage. As with any wire feed welding process using a constant voltage power source, the electrode wire feed rate is the most significant factor in regulating the ESW welding amperage. As long as the weld groove geometry is constant, electrode wire feed speed should not be used to correct amperage during welding. See O12.7 for information about regulating current by means of flux addition.

O12.6 Travel Speed. Travel speed is not controlled independently for ESW but is a consequence of other parameters, such as electrode wire feed speed, voltage, and the number and size of electrodes. It is the primary variable controlling the quality of the weld.

The allowable operating range is the shaded region in Figure O.4; the dashed line shows the target speed.

Q12.7 Flux and Slag. Code requirements for flux addition are contained in 6.22.10. ESW generates heat through resistance to electrical current passing through the molten slag pool. Any variation in slag pool temperature or depth changes its electrical resistance and the welding amperage. Slag pool depth should be controlled by adjusting the flux feed rate to make minor amperage adjustments during welding.

Since the slag that forms between the weld face and cooling shoe is the only normal cause of slag consumption, the volume of flux addition during welding is very small, constant, and the same for any thickness of steel being welded. Automatic flux feed rate during welding is typically about 5.5 g [0.2 oz] per minute. The flux feed rate should be governed by the characteristics of the welding amperage stability after the weld starting phase has achieved stable operating conditions.

O12.8 Preheat. Code requirements for preheat are contained in 6.2.1, 6.17.5, and 6.22.11. Preheat is not specified because of the high heat input characteristic of this process. Base metal and retaining shoes may be required to be heated to avoid condensation when metal temperature is below the atmospheric dew point, but that is not considered preheat. As accelerated cooling provides improved mechanical properties in ESW, it is better not to preheat the steel.

O12.9 Starting. Code requirements for starting are contained in 6.22.9. The volume of flux required to establish the typical 19 mm to 32 mm [3/4 in to 1-1/4 in] slag pool depth is approximately 90 g to 100 g [3.2 oz to 3.5 oz] per 25 mm [1 in] of weld groove thickness. Approximately 1/3 of the total volume should be added to the weld groove prior to weld starting, which will result in a flux layer of approximately 12 mm [1/2 in] in the sump. The balance should be added to the weld pool gradually during the first minute after the weld initiation.

The welding controls should be set for the specified voltage and electrode feed speed even though the voltage during the run-on phase of the weld will not match the procedure requirement. Resistance variations due to arcing, melting of the flux, and the starting sump geometry and tack welds all affect the amperage and voltage stability.

Code requirements for restarts are contained in 6.22.15.

O12.10 Form Factor. The form factor is the ratio of the maximum width of the weld bead to the maximum depth of the molten metal. The maximum width is the root opening plus the depth of fusion. The form factor affects the solidification pattern of the weld bead. Improper form factors can lead to various kinds of cracking. The root opening and welding voltage affect the maximum width of the bead, and the amperage affects the depth of the molten metal. Proper control of welding parameters is essential to ensure a proper form factor.

O12.11 Electrode Oscillation. Electrode oscillation is prohibited per 6.22.12.

O12.12 Joint Opening. Code requirements for joint (root) opening are contained in 6.22.1.

O12.13 Work Leads. Work leads must be sufficient to conduct the welding currents involved. At least two work leads should be used, and one lead attached to each side of the joint, at the bottom near the sump. This will minimize the effects of magnetic interference.

O13. Inspection

Inspection requirements are contained in 6.22.13 and Clause 8. This code requires that production welds made with ESW-NG be inspected with both RT and UT. Regardless of the method of welding, inspection processes have different levels of sensitivity to various weld discontinuities. Historically, UT was known to be incapable of identifying as rejectable extreme levels of piping porosity in ESW welds. While the controls for ESW-NG should be sufficient to preclude the formation of this type of porosity, RT is required to ensure detection of these discontinuities. However, RT is less sensitive to small cracks and planar discontinuities than is UT. To be conservative, both forms of inspection are required.

O14. Repair

O14.1 General. Code requirements for repair are contained in 6.22.14. Removal of an incomplete weld must leave a sound weldable base metal surface. Completely removing the HAZ is unnecessary as subsequent welding will consume it.

O14.2 Interrupted Welds. Code requirements for interrupted welds are contained in 6.22.16.

O14.3 Restarts. Code requirements for restarts are contained in 6.22.15. Any weld metal within 75 mm [3 in] of a restart cannot be part of the final weldment. This includes the top 75 mm [3 in] of the interrupted weld, and 75 mm [3 in] of the root/sump region of the reinitiated weld. This situation may arise when several flanges are cut (ripped) from a single weldment. The flange segment that contains the restart cannot be used, but may be repaired in accordance with 6.22.16.

O15. Qualifications

O15.1 Welding Procedure. Code requirements for WPS qualification are contained in 6.18.1, and 7.15 through 7.20.

O15.2 Welding Operator. Code requirements for operator qualification are contained in Clause 7, Part B.

O16. Weld Quality

Code requirements for weld quality are contained in 6.22.14 and 8.26.

O17. Troubleshooting Guide

O17.1 Porosity. Porosity may result from the use of wet, oily, rusted or otherwise contaminated electrodes, guides, insulators, flux, sumps, run-off tabs, or the base metal. Condensation on the water-cooled shoes, or leaks in the water lines that lead to the shoes, may contaminate the joint with water that may lead to porosity.

O17.2 Centerline Weld Cracking. Centerline weld cracking is typically solidification cracking. Centerline cracking is typically associated with a metallurgically susceptible weld metal and high rates of travel speed. Improper shape factors can contribute to cracking, as can higher levels of carbon, sulfur and phosphorous, whereas manganese and silicon help to reduce cracking tendencies. These alloying elements can come from the electrode, consumable guides, sumps, base metal, and run-off tabs.

O17.3 Incomplete Fusion at Weld Toes. Incomplete fusion at the weld toes is typically due to an off-centered consumable guide. Excessive cooling of the weld surface by the retaining shoe or improper retaining shoe configurations or positioning may also contribute to this type of discontinuity.

O17.4 Incomplete Fusion to One Groove Face. When incomplete fusion occurs, it typically occurs only on one groove face. This discontinuity is associated with insufficient heat received by one of the plates due to uneven heat distribution between the plates. An offset consumable guide may lead to this condition, as can excessive cooling of one side of the joint. Attaching welding leads to one member only may result in magnetic interference that results in incomplete fusion on one groove face.

O17.5 Overlap and Poor Fusion. Overlap and poor fusion are typically associated with improperly prepared grooves in the retaining shoe. Overlap can also occur due to off-center placement of the retaining shoe.

O17.6 Sump Melt-Through. Melt-through in the sump is typically the result of improper sump geometry where the bottom of the sump is too thin for the welding currents involved.

O17.7 Copper Pickup. Copper pickup is due to arcing between the consumable guide and the copper retaining shoe. This occurs when the consumable guide is not centered properly, or when the guide is not of the proper size, or when the guide is not rigidly positioned within the joint. Insulators can be spaced more closely to prevent the consumable guides from arcing against the copper shoes.

O17.8 Metal Spillage. Metal spillage occurs when the retaining shoes are not properly fitted to the base metal. Improper fit may be due to variations in the base metal flatness, warpage of retaining shoes, movement of the shoes during welding, and improper alignment of the two pieces of base metal being joined.

O17.9 Electrode Wander. Electrode wander may occur when electrodes are not properly straightened, or when the consumable guides are not positioned rigidly within the joint.

O17.10 Arcing to Groove Faces. The consumable guide can arc to the weld groove faces. This occurs when the consumable guide is not centered properly, or when the guide is not of the proper size, or when the guide is not rigidly positioned within the joint. Insulators can be spaced more closely to prevent the consumable guides from arcing against the groove face. See O5.8.3 of this annex.

O17.11 Hourglass Nugget Shape. With ESW-NG, this occurs only when multiple electrodes are used and is due to improper consumable guide configurations. The hourglass nugget shape is due to uneven heat distribution across the weld nugget, with thermal energy concentrated around the electrodes.

Table O.1
Example ESW-NG Consumable Guide Configurations

Plate Thickness, mm [in]	Guide Width, mm [in]	Number of Electrodes	Electrode Separation, mm [in]
25–32 [1–1-1/4]	18 [3/4]	1	N/A
32–65 [1-1/4–2-1/2]	25–38 [1–1-1/2]	1	N/A
50–65 [2–2-1/2]	38 [1-1/2]	1	N/A
50–75 [2–3]	38–60 [1-1/2–2-1/4]	2	25 [1]
57–90 [2-1/4–3-1/2]	45–65 [1-3/4–2-1/2]	2	25 [1]
75–115 [3–4-1/2]	65–100 [2-1/2–4]	2	50 [2]

Note: Examples of consumable guide configurations are shown in Figure O.1.

Table O.2
Example Operating Conditions for ESW-NG of ASTM M270M/M270 (A709/A709M) Grades 250 [36], 345 [50], 345S [50S], and 345W [50W]

Plate Thickness, mm [in]	Starting Flux, g [oz]	Number of Electrodes	Electrode Speed, cm/min [ipm]	Current Range (A)	Welding Speed, mm/min [ipm]
25 [1]	85 [3]	1	580 [230]	600–650	75 [3]
32 [1-1/4]	100 [3.5]	1	650 [255]	650–700	67 [2-5/8]
38 [1-1/2]	130 [4.5]	1	710 [280]	790–850	65 [2-1/2]
45 [1-3/4]	140 [5]	1	785 [310]	850–910	55 [2-1/4]
50 [2]	170 [6]	1	860 [340]	900–950	50 [2]
50 [2]	170 [6]	2	430 [170]	900–980	50 [2]
57 [2-1/4]	185 [6.5]	2	540 [210]	1050–1210	48 [1-7/8]
65 [2-1/2]	215 [7.5]	2	590 [230]	1170–1310	43 [1-3/4]
70 [2-3/4]	230 [8]	2	630 [245]	1270–1370	41 [1-5/8]
75 [3]	260 [9]	2	665 [260]	1340–1470	38 [1-1/2]

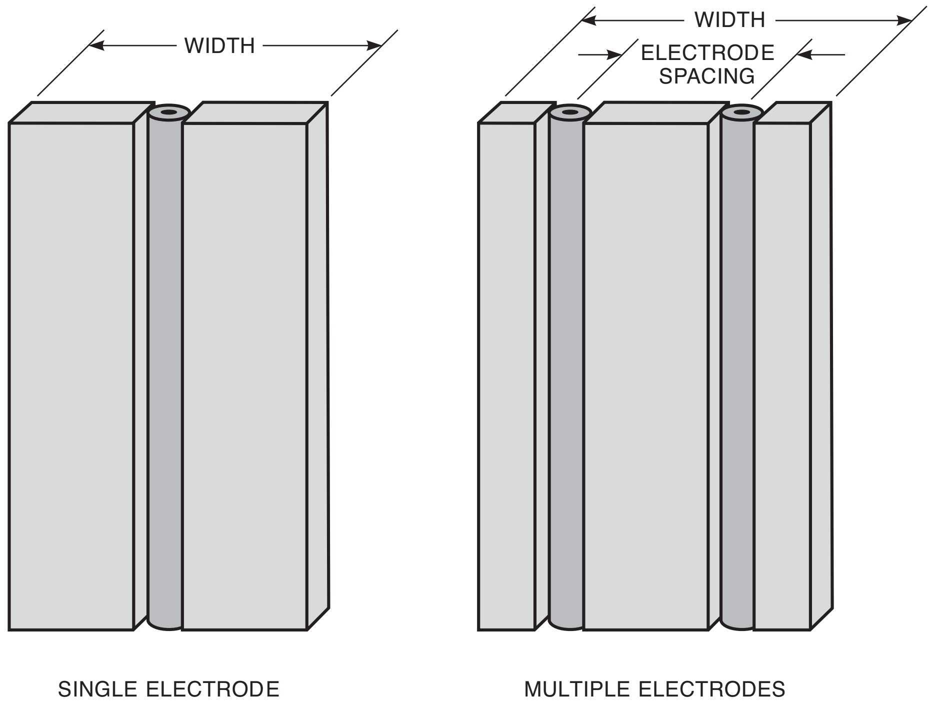

Figure O.1—ESW Single and Multiple Guide Configurations

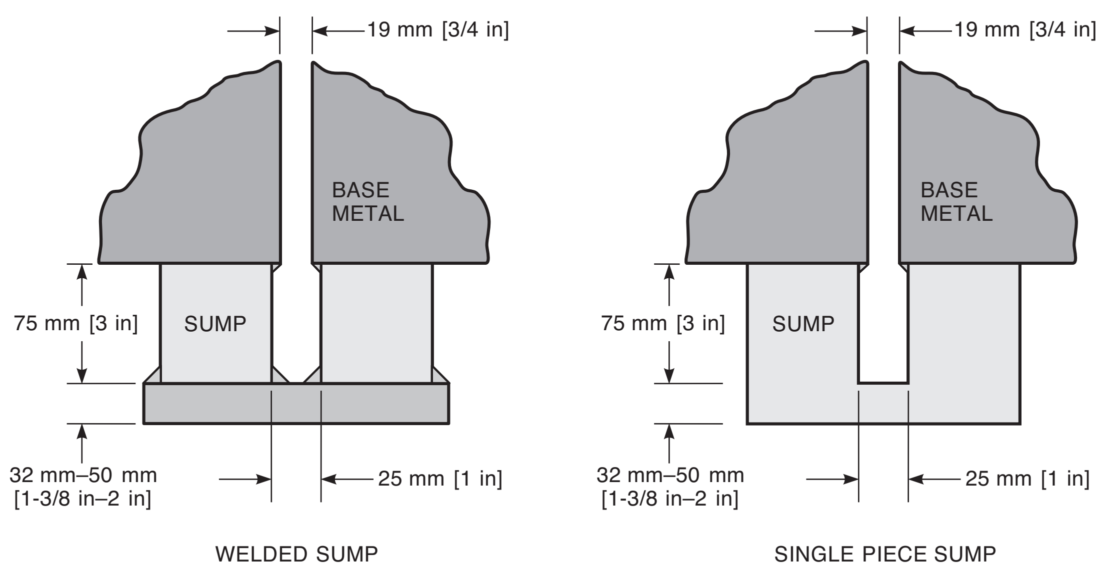

Figure O.2—ESW Welded and Single Piece Sumps

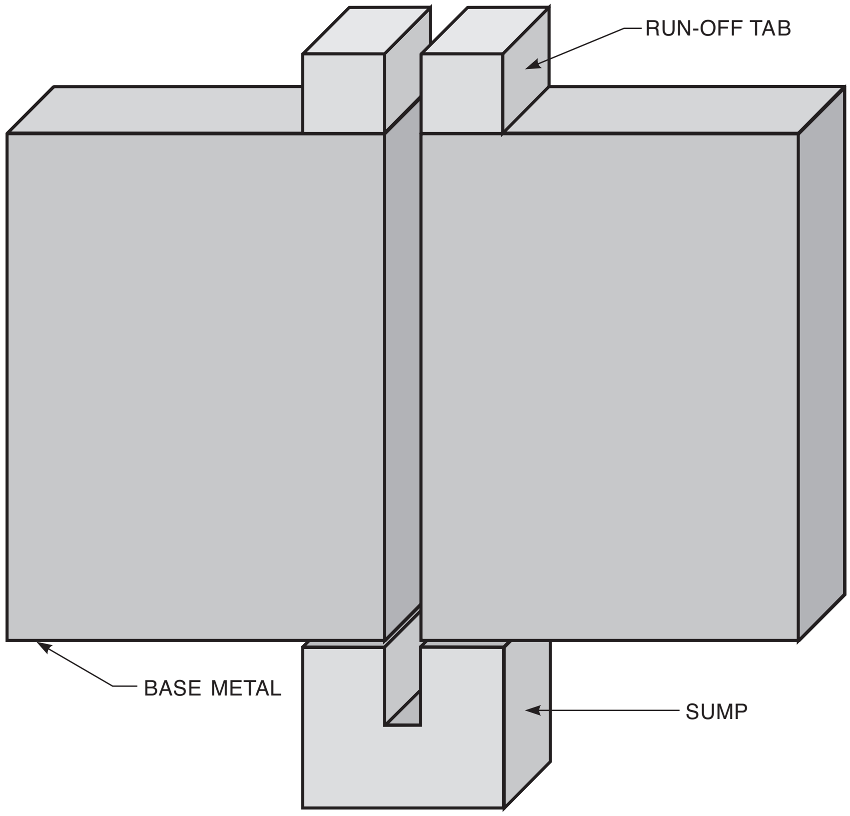

Figure O.3—ESW Sump and Run-Off Tab Illustration

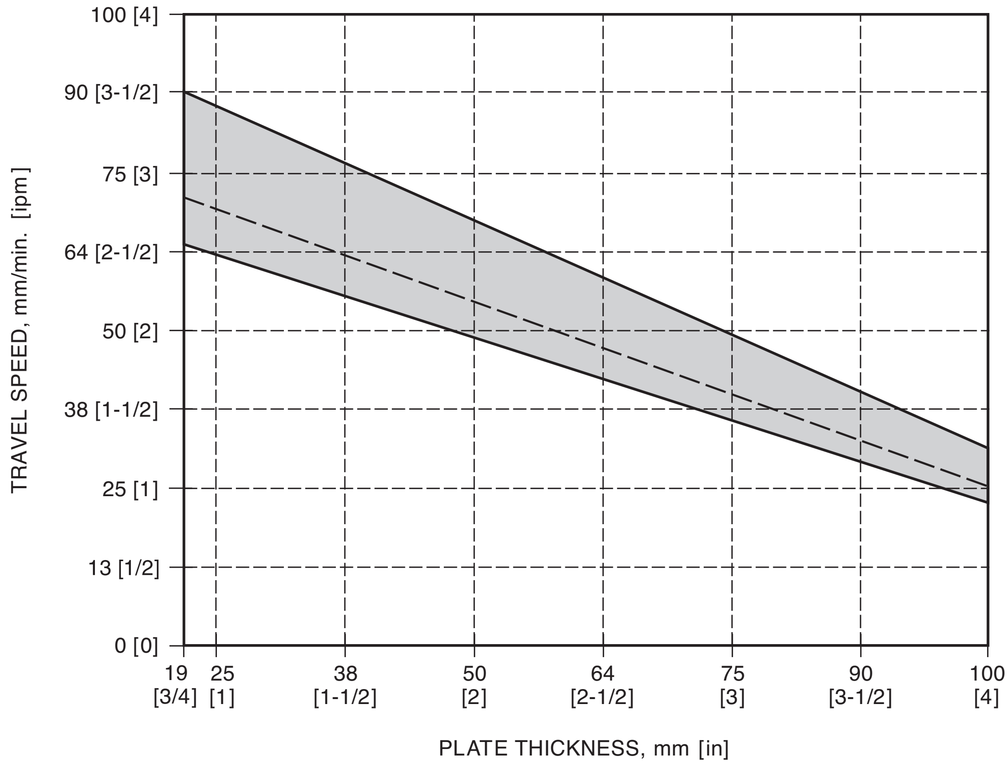

Figure O.4—Allowable Operating Ranges for ESW-NG

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Annex P
Requesting an Official Interpretation of a Joint AASHTO/AWS Standard

This annex is not part of this standard but is included for informational purposes only.

P1. Introduction

The following procedures are here to assist standard users in submitting successful requests for official interpretations to AWS standards. Requests from the general public submitted to AWS staff or committee members that do not follow these rules may be returned to the sender unanswered. AWS reserves the right to decline answering specific requests; if AWS declines a request, AWS will provide the reason to the individual why the request was declined.

P2. Limitations

The activities of AWS technical committees regarding interpretations are limited strictly to the interpretation of provisions of standards prepared by the committees. Neither AWS staff nor the committees are in a position to offer interpretive or consulting services on (1) specific engineering problems, (2) requirements of standards applied to fabrications outside the scope of the document, or (3) points not specifically covered by the standard. In such cases, the inquirer should seek assistance from a competent engineer experienced in the particular field of interest.

P3. General Procedure for all Requests

P3.1 Submission. All requests shall be sent to the Director, AWS Standards Development. For efficient handling, it is preferred that all requests should be submitted electronically through standards@aws.org. Alternatively, requests may be mailed to:

Director
Standards Development
American Welding Society
8669 NW 36 St, # 130
Miami, FL 33166

P3.2 Contact Information. All inquiries shall contain the name, address, email, phone number, and employer of the inquirer.

P3.3 Scope. Each inquiry shall address one single provision of the standard unless the issue in question involves two or more interrelated provisions. The provision(s) shall be identified in the scope of the request along with the edition of the standard (e.g., D1.1:2006) that contains the provision(s) the inquirer is addressing.

P3.4 Question(s). All requests shall be stated in the form of a question that can be answered 'yes' or 'no'. The request shall be concise, yet complete enough to enable the committee to understand the point of the issue in question. When the point is not clearly defined, the request will be returned for clarification. Sketches should be used whenever appropriate, and all paragraphs, figures, and tables (or annexes) that bear on the issue in question shall be cited.

P3.5 Proposed Answer(s). The inquirer shall provide proposed answer(s) to their own question(s).

P3.6 Background. Additional information on the topic may be provided but is not necessary. The question(s) and proposed answer(s) above shall stand on their own without the need for additional background information.

P4. AWS Policy on Interpretations

The American Welding Society (AWS) Board of Directors has adopted a policy whereby all official interpretations of AWS standards are handled in a formal manner. Under this policy, all official interpretations are approved by the technical committee that is responsible for the standard. Communication concerning an official interpretation is directed through the AWS staff member who works with that technical committee. The policy requires that all requests for an official interpretation be submitted in writing. Such requests will be handled as expeditiously as possible, but due to the procedures that must be followed, some requests for an official interpretation may take considerable time to complete.

P5. AWS Response to Requests

Upon approval by the committee, the interpretation is an official interpretation of the Society, and AWS shall transmit the response to the inquirer, publish it in the *Welding Journal*, and post it on the AWS website.

P6. Telephone Inquiries

Telephone inquiries to AWS Headquarters concerning AWS standards should be limited to questions of a general nature or to matters directly related to the use of the standard. The *AWS Board Policy Manual* requires that all AWS staff members respond to a telephone request for an official interpretation of any AWS standard with the information that such an interpretation can be obtained only through a written request. Headquarters staff cannot provide consulting services. However, the staff can refer a caller to any of those consultants whose names are on file at AWS Headquarters.

Commentary on Bridge Welding Code

8th Edition

Prepared by the
AWS D1 Committee on Structural Welding

Under the Direction of the
AWS Technical Activities Committee

Approved by the
AWS Board of Directors

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Foreword

This foreword is not part of the Commentary of this standard but is included for informational purposes only.

The AASHTO/AWS *Bridge Welding Code* is produced to provide, to the greatest extent possible, a nationally accepted single source document that may be used as a bridge welding specification by all AASHTO member organizations constructing steel bridges. Although the proper title for the *Bridge Welding Code* is the AASHTO/AWS D1.5M/D1.5 *Bridge Welding Code*, it will be referred to as the "code" in this Commentary.

This Commentary has been developed to explain the basis for code provisions, and to provide sufficient information on each subject to help those involved in bridge construction to effectively use the code.

The beginning of the code was a combination of the ANSI/AWS D1.1-88 *Structural Welding Code—Steel* and the AASHTO *Standard Specification for Welding of Structural Steel Highway Bridges*, Third Edition, 1981. Prior to the acceptance of the first *Bridge Welding Code*, designated ANSI/AASHTO/AWS D1.5-88, all states using Federal Highway funds to construct steel bridges were required to use the AWS and AASHTO specifications in concert, as well as any applicable FHWA Special Provisions. In addition, many states imposed special provisions of their own.

The primary goals of the code are to (1) ensure a high level of safety in welded steel structures subject to truck or railroad loads and (2) avoid practices that might reduce the useful life of steel bridges or unnecessarily increase the cost of future maintenance. Secondary goals include making the specifications more effective in achieving the goals stated above and the reduction of unnecessary costs.

The goal of improved safety is primarily addressed through improved fracture safety, attained through better specifications for the quality of materials and by the workmanship needed to ensure fracture resistance and good fatigue performance. Other safety features, for example the avoidance of buckling, are addressed by design specifications and workmanship tolerances. The goal of reducing unnecessary costs is achieved by specifying only what is necessary to ensure safety and good performance, and by providing universal testing procedures to reduce the duplication of effort that unnecessarily increases the cost of construction.

It is difficult to work with multiple specifications, produced by different groups, sometimes specifying different requirements for the same task, particularly when published on different schedules. This often inhibits a thorough understanding and full utilization of the specifications. When all AASHTO member organizations use the same basic welding specification, fabricators, erectors, and Inspectors, representing both the Contractor and the Owner, are in a better position to interpret code provisions properly and to conform to code requirements. When States have the same basic requirements for essentially the same tasks, better understanding and utilization of the specifications by both Owner and Contractor representatives will improve quality while costs are reduced or contained.

Duplication of effort in testing of welders and WPSs is discouraged by the Bridge Welding Subcommittee, AASHTO, and FHWA. Procedures have been developed for the qualification of WPSs with a minimum of complexity and effort, yet with sufficient detail to ensure reliability.

The Commentary attempts to make clear the reasons for differences that exist between the AASHTO/AWS D1.5M/D1.5 *Bridge Welding Code* and the AWS D1.1 *Structural Welding Code—Steel*. The most obvious reason for differences is that Owners of highway and railway bridges have elected to take steps in the selection of materials and in the qualification and control of WPSs to ensure that all steel bridge members and welds have sufficient toughness to resist brittle fracture. Additional steps are taken in design and construction of bridges to avoid conditions that may lead to hydrogen-induced or fatigue cracking. The methods used to achieve these goals are based on the control of welding heat inputs and attendant cooling rates, and the minimizing or avoidance of stress concentrations from weld or base metal discontinuities. Control of transformation cooling rates, in addition to control of weld and base metal chemical composition, ensures that required mechanical properties are obtained in welds and adjacent HAZs. Heat input control, in addition to control of preheat and interpass temperatures, ensures that the base metal is not degraded as a result of permanent or temporary welds. These same controls provide safeguards against hydrogen-induced cracking.

To date, AWS D1.1 has not incorporated methods of welding heat input control, other than to impose limitations on welding variables for those WPSs required to be qualified by test, and to specify technique limitations for other WPSs that are considered prequalified.

Standards necessary to ensure fracture safety in statically loaded structures are less restrictive than those standards necessary to ensure fracture safety in cyclically loaded structures. Statically loaded structures, such as buildings, are stressed with variable loadings at relatively slow strain rates. Loadings such as wind loads and floor loads are treated as static loads for design purposes. Bridges are cyclically loaded structures, also called dynamically loaded structures, and are stressed with full design forces more frequently, with enough applications of design loading to induce fatigue in the member or component. Strain rates may also be higher in cyclically loaded structures, although a lesser factor in fatigue life. In bridges and other cyclically loaded structures, live load stresses may initiate or extend fatigue cracks. This is rarely a problem in statically loaded structures, or in structures where neither the number of cycles of loading or the range of stress is sufficient to cause fatigue damage.

AASHTO bridges are designed for specific numbers of applications of the design load. Each application and removal of the maximum design load produces the design stress range in the bridge member. Fatigue design is based on the stress range and the number of cycles of loading.

Fracture safety is important for all metal structures. The underlying principles of metallurgy, fatigue, and fracture are the same for all cyclically loaded steel structures. In this code, emphasis is placed on qualification and control of WPSs and avoidance of hydrogen and fatigue cracks.

The safety of steel bridges is largely dependent on resistance to brittle fracture. Fracture is avoided by improving resistance to fatigue cracking by minimizing or avoiding stress concentrations in design and construction, and by eliminating conditions that might cause hydrogen-induced or solidification cracks. Resistance to brittle fracture is significantly improved by good weld and base metal toughness, as well as avoiding notches and using good design and details. This code addresses improved workmanship, weld soundness, and fracture toughness to ensure the fracture safety of steel bridge members.

Nonredundant fracture critical steel bridge members require a higher level of quality in materials and workmanship to ensure safety equivalent to that of redundant bridge members. The 1988 edition of the code made no special provisions for the construction of Nonredundant Fracture Critical Members, FCMs. The AASHTO *Guide Specification for Nonredundant Fracture Critical Steel Bridge Members* was used to construct all FCMs. The *Bridge Welding Code* was revised in 1995 to include a Fracture Control Plan.

Since fracture avoidance, particularly avoidance of brittle fracture, is a primary goal of this code, it is helpful to briefly review the relationship between workmanship quality, weld and base metal discontinuities, fatigue cracks, toughness, and brittle fracture.

Brittle fracture is the abrupt rupture of a member or component loaded in tension, whether the tension is applied or residual tension, and whether from applied axial or flexural loading. Failure is instantaneous and generally will not arrest if the load initiating the brittle fracture is sustained as the fracture progresses. When brittle fracture occurs in a redundant bridge member, the loading is generally transferred to adjacent members and general collapse does not occur. By definition, in nonredundant members, brittle fracture may cause collapse of the structure. Brittle fracture of a tension member is analogous to buckling of a compression member: rarely will either stop before failure is complete if the loading is maintained. However, this code does not address buckling of steel bridge members, as buckling is primarily a design or maintenance consideration. Fracture avoidance is stressed throughout the code because brittle fractures may result from what may have initially appeared to be small, or innocuous discontinuities, prior to fatigue crack initiation and propagation to critical size.

The workmanship provisions of the code dictate that notches are to be avoided. Sharp or deep notches are particularly harmful, whether on the surface or buried within the weld or base metal. Discontinuities at a surface are more critical than equivalent discontinuities entirely surrounded by sound metal, but all may cause failure of the part or structure. Standards are established for the soundness of welds that limit the size, location, and sharpness of weld discontinuities.

There is no fatigue crack initiation or propagation without a stress concentration to amplify stress. Stress amplification by weld or base metal discontinuities is proportional to the size and sharpness of the discontinuity. Cracks are prohibited because they are the sharpest of discontinuities and attract high stress concentrations. The quality of welds specified in Clause 5 of the code take this into account, and also provide standards for workmanship and weld soundness that help ensure fracture safety in a bridge fatigue environment.

Under the provisions of this code, weld brittle fracture is avoided through careful attention to items that might reasonably be anticipated to lead to the initiation of cracks from any source. If hydrogen is properly controlled, although tensile stress and a susceptible microstructure are present, there should be no hydrogen-induced cracking. If proper base metal and welding consumables are used and proper WPSs are followed, there should not be cracking.

Cracks are routinely prohibited by all specifications for welding of steel structures. In addition to prohibiting cracks and controlling the quality of workmanship, this code controls the use of temporary welds that may initiate brittle fracture as a result of their hardened HAZs.

Fatigue crack prevention is depends on high fracture toughness, good design, and good workmanship that minimizes stress concentrations. The maximum crack or discontinuity size that can be sustained by a steel bridge member, subjected to maximum stress at its lowest anticipated service temperature, depends on the toughness of the steel base metal or weld metal at the crack tip for the given temperature. AASHTO specifies the minimum fracture toughness of steel plates and shapes used to construct bridge members. The minimum toughness of filler metals is specified in the filler metal specifications, and the toughness of the production weld is specified in the code. Weld and base metal mechanical properties are protected from degradation by code requirements for qualification and control of welding procedures. Good toughness ensures that cracks, created by any condition and possibly extended by fatigue, may grow to discoverable and therefore repairable size without causing a brittle fracture.

Weld hardness and toughness depend on the chemical composition of the base metal and weld metal, the solidification mechanism affected by cooling rate, and the thermal cycles to which the weld is subjected. HAZ hardness and toughness also depend on base metal chemical composition and thermal cycles. Since base metal chemical composition is often more hardenable than weld metal chemical composition, the base metal HAZ may be more sensitive to high cooling rates that cause unacceptable hardening than the weld. The code has been written to protect the hardness and toughness of both welds and HAZs.

Quenched and tempered steels such as AASHTO M 270M/M 270 (ASTM A709/A709M) Grades HPS 485W [HPS 70W] and HPS 690W [HPS 100W], and the high strength filler metals used to match the strength of these steels, may have their strength and toughness affected by excessive welding heat input. Unusually slow cooling rates from excessive preheat and interpass temperatures, combined with high welding heat inputs, may also degrade the mechanical properties of welded joints in these heat treated steels. Fast cooling rates, produced by welding with low welding heat input, combined with low preheat and interpass temperatures, may produce excessive hardness and hydrogen-induced cracking in these same high strength steels. Proper procedures for welding quenched and tempered steels are explained in the Commentary.

Users of the code are encouraged to read all of the code and the Commentary. Together, the two documents are intended to give a complete picture of bridge welding requirements. However, because many people will not have an opportunity to read the complete code and Commentary before starting to use the code, an attempt has been made to explain each specification provision in sufficient detail to make each commentary item self-explanatory. This requires more than a desirable amount of repetition. However, such repetition adds expedience in providing direct and comprehensive clarification of the potential questions of the user, without having to read the entire document. To completely understand Commentary items, the user shall first read the code subclause, figure, etc. on which the Commentary is based. Code text is not repeated in the Commentary.

The Commentary is an informative addition to the *Bridge Welding Code*. Its purpose is to explain, provide history, and to educate. No statement in the Commentary modifies the code or is binding upon code users in the absence of specific code provisions. Each subclause in the code does not require a comment. Where individual specifications are considered self-explanatory and fully understood, no commentary is provided. The principles of welding and fracture avoidance are emphasized to a greater extent than provisions for mechanical testing of welds or NDT, which are not new material in this code.

All references to numbered subclauses, tables, figures etc. shall, unless otherwise indicated, refer to the identically numbered subclause, table, or figure in the AASHTO/AWS D1.5M/D1.5, *Bridge Welding Code*. References in the Commentary are prefixed with a "C-" to indicate they are commentary material.

Normative annexes are a part of the code. The code also contains useful but informative information that is provided to assist users of the code. This information is contained in both normative and informative annexes that use alphabet letters A, B, C, and so forth. Annex L, Description of Common Weld and Base Metal Discontinuities, is provided to help code users to identify, describe, and evaluate common weld and base metal discontinuities.

Code writing is a continuing process. Provisions that code users feel should be corrected or improved should be called to the attention of the AASHTO/AWS Bridge Welding Subcommittee (see Annex P).

Commentary on Bridge Welding Code

C-1. General Provisions

C-1.1 Application

This AASHTO/AWS *Bridge Welding Code* is specifically written for the use of states, provinces, and other governmental members associated with AASHTO. Other organizations that have a need to construct welded steel bridges to support dynamic loads should study the relationship between the fatigue loads imposed on their structure and the design truck loads and number of cycles provided for in the AASHTO *Standard Specification for Highway Bridges*.

The AASHTO/AWS *Bridge Welding Code*, AASHTO/AWS D1.5, is referred to as “the code” throughout the text of the *Bridge Welding Code* and this Commentary. The AWS D1.1 *Structural Welding Code—Steel*, and other specifications of the American Welding Society also frequently use the term “code” when referring to provisions of individual specifications. Care should be taken to avoid confusion in the use of this common term. When the term “code” is used in the *Bridge Welding Code* and this Commentary, it only refers to the AASHTO/AWS D1.5 *Bridge Welding Code*.

C-1.1.1 This code specifies the material and workmanship requirements necessary to shop and field construct welded steel highway bridges. Specifications are provided for the NDT of welds and base metal when:

(1) required by the code or contract documents, or

(2) ordered by the Engineer.

The design of bridges is not described in the code. This information is specified in the AASHTO *Standard Specifications for Highway Bridges* or the AASHTO *LRFD Bridge Design Specifications*.

C-1.1.2 The quality of workmanship described in the code is based on what was once called “good practice in a modern bridge shop.” The code is a “workmanship” specification, meaning the quality required is based upon what is readily achievable. “Suitability for service” is the minimum quality required for the member or weld to perform its intended function.

The Engineer may specify or accept workmanship and weld quality standards that are different than those described in the code. Workmanship and weld quality standards that differ from code requirements should be specified in the contract documents so there is no need to negotiate the cost of additions or deletions to the work during fabrication or erection.

Experience has shown that the quality of thermal cut surfaces, welds, and the effects of other fabrication practices on workmanship and finish can affect bridge fatigue life, safety, and the extent of future maintenance. In some cases, the quality of a completed production weld may not meet all the requirements of the code. The Engineer may also use engineering judgment to accept the quality of the weld as completed, or with modified repairs. When such judgment is used, evaluation of suitability of service using modern fracture mechanics techniques, a history of satisfactory service in similar structures, or experimental evidence is recognized as a suitable basis for alternate acceptance criteria. Unnecessary and/or improper repairs made by welding may cause more serious discontinuities, distortion, and cracks.

C-1.1.3 The Engineer is the individual with the authority to approve shop drawings, materials, WPSs, modifications to the requirements of the contract documents, and other matters that require approval of the agency represented. The Engineer is considered to be the Owner or Owner’s representative, and may delegate this authority to others.

C-1.1.4 Contractor. "Contractor" is the proper term for the person or firm that is responsible for performing the work as described in the code. However, when the work is expected to be done in a bridge fabricating shop, the term "fabricator" may be used interchangeably. When work is expected to be done in the field, the term "erector" may be used instead of Contractor.

C-1.2 Base Metal

C-1.2.1 Specified Base Metal. The code lists AASHTO approved base metals in 1.2.2. AWS D1.1 lists other carbon and low-alloy steels that are weldable. The contract documents may specify any steel product that the Engineer considers suitable for the intended purpose. Engineers should specify, when possible, only listed steels, and if not, only steel products known to be weldable. A steel is considered weldable when it can be joined by welding without unusual difficulty. The steel specified should also be readily available for purchase.

Structural steel plates and shapes are subject to the delivery requirements of ASTM A6/A6M as provided in the AASHTO M 270M/ M 270 (ASTM A709/A709M) base metal specifications. Dimensional tolerances, allowable discontinuities, and methods of conditioning (repairing) in the mill are as described in the delivery requirements. If there are special requirements for straightness, surface finish, overrun or underrun in thickness, restrictions on conditioning by welding at the mill, or any other project specific requirements, they should be specified in the contract documents. Provisions for the repair of base metal are described in 5.2.

The dimensional tolerances for fabricated structural steel are as described in Clause 5 of this code and are independent of base metal delivery requirements. In some cases, ASTM A6/A6M mill tolerances will exceed those applicable for bridge construction, in which case it may be necessary to correct the material deficiency or to replace the material.

C-1.2.2 Approved Base Metals. The base metals listed are steels approved for use in welded steel bridge construction. The list is reviewed periodically and additions may be made to the list as approved by AASHTO. Each steel product, plate, shape, bar, etc., is listed by the AASHTO materials specification designation and corresponding ASTM specification.

AASHTO M 270M/M 270 steels of a designated grade are essentially the same as ASTM A709/A709M steels of the same grade. AASHTO M 270M/M 270 (ASTM A709/A709M) steels are enhanced versions of the structural steels used in buildings and other steel structures. The principal enhancement is in the area of toughness, with optional provisions applicable to Fracture Critical Members. Common ties exist between the following steel designations:

(1) Grade 250 [36]	ASTM A36/A36M
(2) Grade 345 [50]	ASTM A572/A572M Grade 345 [50]
(3) Grade 345S [50S]	ASTM A992/A992M
(4) Grade 345W [50W]	ASTM A588/A588M Grade A or B

Base metal toughness is a supplemental of AASHTO M 270M/M 270 (ASTM A709/A709M) for main members or components in tension. Filler metal toughness is a requirement of the AWS electrode classifications described in this code. Weld metal CVN test value requirements are described in Table 7.3, based on AASHTO Temperature Zone I, II, or III.

C-1.2.3 Thickness Limitations. The thickness limitations of this subclause deal only with minimum thickness. This code provides basic welding specifications for steel thicknesses equal to or greater than 3 mm [1/8 in]. Proper controls should be exercised over welding heat input, preheat and interpass temperature depending upon steel thickness and the relative configuration of the thicknesses of the joint.

For sections thinner than 3 mm [1/8 in], AWS D1.3/D1.3M, *Structural Welding Code—Sheet Steel*, should be consulted. However, this document is based on static applications, and does not contain special provisions specific to bridge welding.

The maximum material thickness for steel governed under AASHTO M 270M/M 270 (ASTM A709/A709M) is 100 mm [4 in]. However, the majority of the current code provisions were drafted based on steel specifications not subjected to this maximum thickness limit. The Engineer should decide if maximum thicknesses limitations other than 100 mm [4 in] should be used, and specify any special welding requirements for heavier plates in the contract documents.

C-1.3 Welding Processes

C-1.3.1 Welding processes that are not listed in the code may be used with the approval of the Engineer. Any welding process and WPS that provides for the use of that process may be used, provided the specific weld joint details and controls of welding variables that have been qualified by tests are acceptable to the Engineer. Consideration of welding processes not described in the code is allowed, but acceptance by one agency does not obligate other agencies to approve use of the process.

C-1.3.4 See Annex O.

C-1.3.6 Short circuiting GMAW-S is restricted for the construction of steel bridge members because of its propensity to form fusion discontinuities called cold laps. Properly qualified GMAW WPSs, operated in the spray or globular mode of metal transfer are allowed (see 6.13.4). Also see Annex M for a description of GMAW-S.

C-1.3.7 Welding of Ancillary Products. This provision was added to the 1995 code to allow the fabrication of the listed items and similar items, as determined by the Engineer. Such items are not usually subjected to design tensile stresses and may not be welded to the tensile stress region of stress-carrying members. In addition to the prequalification of SMAW WPSs, the requirement for full WPS qualification is also relieved for SAW, FCAW, and GMAW processes when used to weld these members, provided the manufacturer's recommendations for WPS variables are followed, and the other portions of the code are satisfied. When a product deemed ancillary by the Engineer is welded to the compression region of a stress-carrying member, then the full requirements of WPS qualification need to be satisfied for the welds connecting the product to the stress-carrying member.

C-1.8 Standard Units of Measurement

This code has two units systems: metric and U.S. Customary. Throughout the code, the user will find dimensions in SI (metric) Units followed by U.S. Customary Units in brackets [ ]. The U.S. Customary Units are "hard" conversions of the SI Units; that is, each is a carefully considered rational value, as opposed to a "soft" conversion value that has been simply adjusted from the SI value using a conversion factor. For example, the soft conversion of 25 mm would be 0.984 in, and the hard conversion would be 1 in. It is inappropriate to pick and choose between SI and U.S. Customary tolerances; each system of units should be used as a whole, and the system used should be the same as that used in the shop drawings.

In terms of WPSs, fabricators should not be required to rerun PQRs for a change in units. However, WPSs should be drafted in the appropriate units.

C-1.9 Welding Procedure Specifications (WPSs)

Each weld is to be made using an approved WPS that is based on a PQR. The results of mechanical tests of weld specimens verify that the strength, ductility, and toughness required by the code have been produced in the test welds. Welding in conformance with the provisions of an approved WPS, which is in turn based on an approved PQR, provides assurance that production welds will have the strength, ductility, and toughness required by the code.

Two exceptions are made to this general requirement:

(1) SMAW that has a minimum specified yield strength less than 620 MPa [90 ksi] may be used without qualification testing, provided the WPS conforms to the manufacturer's recommendations for weld variables, and the welding is to be done in conformance with the provisions of Clause 6, Part B (see 7.1.1).

(2) Ancillary product welding is exempted from testing per 1.3.7.

C-1.10 Mechanical Testing

AWS B4.0 or B4.0M, *Standard for Mechanical Testing of Welds*, is to be the standard for test apparatus and test specimens. In areas where the provisions of B4.0 or B4.0M and the *Bridge Welding Code* conflict, this code should take precedence.

C-4. Design of Welded Connections

Part A
General Requirements

C-4.1 Drawings

C-4.1.1 The drawings referred to in the code include the bridge design drawings or plans and the shop or working drawings. Plans, along with specifications and special provisions, are prepared by the Engineer or Owner, shop drawings are prepared by the Contractor. The plans and shop drawings should describe the required welds by welding symbols or a combination of welding symbols and notes.

The Engineer is encouraged not to detail specific groove weld details for routine welds, but to simply specify the joint penetration (CJP or PJP weld), joint type (butt joint, T-joint, corner joint, etc.), and weld size as necessary. The specific joint details are left to the Contractor. The Contractor, assumed knowledgeable in welding and welding economies, is in the best position to select the details for the welded joints that best fit the Contractor's capabilities and avoid undesirable effects such as excessive distortion.

All approved CJP groove weld joint details produce the same weld joint strength when welded with the same strength filler metal. Unless there is justification to specify a particular process or groove weld configuration, the Contractor should be allowed to determine details during the preparation of shop drawings. Assuming an appropriate prequalified SMAW WPS or qualified WPS is used, the details of welded joints provided in Figures 4.4 and 4.5 are considered standard and therefore exempt from testing, based on a long history of successful performance during welding and in service. The Contractor may propose other joint details that are qualified by tests described in 7.7.5, and the Engineer may approve the joint detail based on weld joint qualification testing.

C-4.1.2 The volume of weld metal deposited and the number of weld passes on the first side of a two-sided groove weld joint, before welding the second side, may significantly affect angular distortion. The second side of the weld joint may need more weld metal than the first side to overcome the distortion produced by shrinkage of the first side weld. Special weld pass sequencing is generally not placed on the plans, but should be included in the WPS and/or on the shop drawings.

Both the Engineer and the Contractor should make efforts to minimize the size of groove welds where possible. This may be done by controlling groove angles and root openings. Groove details should be primarily designed for adequate access for welding and visual inspection, as well as the minimum volume of weld metal, as any excess beyond the minimum will create unnecessary distortion and residual stresses, and may cause lamellar tearing in corner and T-joints.

Residual stresses may be reduced by minimizing the volume of weld metal and by lowering the yield strength of the weld metal to the minimum strength acceptable for the design. Undermatching of weld metal strength is encouraged for fillet welds that are designed to transmit only shear stress.

Some welded joint configurations for corner and T-joints contribute more than others to the risk of lamellar tearing, cracks parallel to the plate surface caused by high localized through-thickness strains induced by thermal shrinkage. The capacity to transmit through-thickness stresses is essential to the proper functioning of some corner and T-joints. Laminations (pre-existing planes of weakness in the base metal) or lamellar tearing may impair this capacity.

Consideration of the problem of lamellar tearing includes design aspects and WPSs that are consistent with the properties of the connected material. In connections where lamellar tearing might be a problem, consideration should be given in design to maximum component flexibility and minimize weld shrinkage strain.

Observing the following precautions may reduce the risk of lamellar tearing during fabrication in highly restrained welded connections:

(1) On corner joints, where feasible, the bevel should be on the through-thickness member.

(2) The size of the weld groove should be kept to a minimum consistent with the design, and unnecessary welding should be avoided.

(3) Subassemblies involving corner and T-joints should be fabricated completely prior to final assembly of connections. Final assembly should preferably be at butt joints.

(4) A predetermined weld sequence should be selected to minimize cumulative shrinkage stresses on the most highly restrained elements.

(5) Undermatching using a lower strength weld metal, consistent with design requirements, should be used to allow higher strain in the weld metal, reducing stress in the more sensitive through-thickness direction of the base metal.

(6) "Buttering" with low strength weld metal, peening, or other special procedures should be considered to minimize through-thickness shrinkage strains in the base metal.

(7) Material with improved through-thickness ductility may be specified for critical connections.

In critical joint areas subject to tensile loading in the through-thickness direction, material should be UT inspected (straight beam) within a lateral distance of twice its thickness from the joint to ensure the absence of existing laminations and significant discontinuities such as metallic and nonmetallic inclusions. In addition, the following precautions should be taken:

(1) The Engineer should selectively specify UT inspection, after fabrication or erection or both, of specific highly-restrained connections critical to structural integrity that could be subject to lamellar tearing.

(2) The Engineer may consider whether minor weld discontinuities or base metal imperfections can be left unrepaired without jeopardizing the structural integrity, as gouging and repair welding will add additional cycles of weld shrinkage to the connection, and may result in the extension of existing discontinuities or the generation of new discontinuities by lamellar tearing.

(3) When lamellar tears are identified and repair is deemed advisable, a special WPS or a change in joint detail may be necessary.

C-4.1.3 Partial joint penetration (PJP) groove welds are limited to joints designed to transmit compression in butt joints with full-milled bearing surfaces, and to corner and T-joints (see 4.14). PJP groove welds also may be used in nonstructural appurtenances such as ancillary products. In butt joints, they may be used to transmit compressive stress, but should never be used to carry tensile stress in bridge members because of short fatigue life. When PJP groove welds are to be used, the effective weld size (S) should be specified on the plans, and the Contractor provides the groove preparation necessary to produce the required weld size.

Longitudinal web-to-flange welds designed for tensile stresses parallel to the weld throat have the same allowable fatigue stress range whether designed as a fillet weld or a CJP groove weld with backing removed. PJP groove welds and CJP groove welds with backing remaining in place have a lower allowable fatigue stress range. The same is true for similar welds carrying tension parallel to the weld throat, as long as the weld axis or weld throat is parallel to the applied stress. This is independent of the fact that the weld may be part of a member that is subject to considerable axial tensile stress and stress range. For example: an axially stressed box section, as long as the box is not designed for torsion about its longitudinal axis. For shear stresses, the AASHTO Specification provides allowable stress ranges for fillet welds only.

There will be no increase in bridge safety as a result of specifying CJP groove welds where PJP groove welds or fillet welds, at considerably less cost, will carry the design stress. Smaller weld volumes, consistent with design stress requirements, create less residual stress and less chance that there will be unacceptable distortion or lamellar tearing. However, the minimum size for fillet welds and PJP groove welds, relative to the thickness of the materials, is also necessary to ensure adequate heat input for full fusion and adequate cooling rates (see Table 4.1 for fillet welds and Table 4.2 for PJP groove welds).

C-4.1.3.1 AWS A2.4, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*, should be used to specify welds using industry standard methodology (see 1.6).

C-4.1.5 All requirements for special inspections or NDT not covered by this code need to be specified in the contract documents. This ensures that required inspections and tests will be performed, avoiding disagreement over minimum weld quality and additional costs (see 8.6.5).

C-4.1.6 AASHTO design specifications allow the use of undermatching weld metal strength for the applications listed in this paragraph. The most common application for undermatching weld metal strength is on higher strength steel (e.g., Grade HPS 485W [HPS 70W] and HPS 690W [HPS 100W], and for fillet welds and PJP groove welds loaded in shear. It is essential that the designer of the weld consider the strength of the weld metal that is used when determining the required weld size. In most cases where undermatching is permissible, it offers the benefits of reduced residual stresses and greater resistance to cracking. The code provides the option for the Engineer to specify matching weld metal, specify undermatching weld metal, or to provide the option to the Contractor to utilize either approach. When the option is given to the Contractor, the design drawings need to show the required weld size for each filler metal strength level. See Ship Structure Committee report SSC-383, "Optimum Weld-Metal Strength for High Strength Ship Structures", Dexter and Ferrell, 1995. for an investigation of the performance of moderately undermatched welds.

Use of filler metal matching the lower-strength side of a hybrid joint is not considered undermatching. See 6.1.1.

In most cases, weld metal classified with minimum specified tensile strength of 70 or 80 ksi will be used for undermatching applications. 70 ksi weld metal is generally preferable, but 80 ksi weld metal is often used for unpainted weathering applications.

Shop drawings are required to show the required weld size, and the required weld strength. To avoid confusion on the shop floor, options should not be shown on shop drawings. If no weld metal strength class is designated, matching weld metal is assumed.

C-4.2 Basic Unit Stresses

Based on AASHTO specifications, the Engineer determines the unit stresses to be used as a basis for design.

C-4.3 Effective Weld Areas, Lengths, Throats, and Sizes

C-4.3.1 Groove Welds. The effective groove weld size was formerly called the effective throat. The effective throat effective size of PJP groove welds is defined in 4.3.1.3, and further detailed and explained in Annex A. The effective size of CJP groove welds is as described in 4.3.1.2.

C-4.3.1.3 The effective PJP groove weld size is based on the geometry of the groove weld joint preparation, the welding process, and welding position. Access for welding at the root of bevel or V grooves and an assumed relative depth of joint penetration is attributed to the various welding processes. It is assumed that penetration to the root is achieved for SMAW, SAW, GMAW, FCAW, ESW, and EGW processes when the groove angle equals or exceeds 60°.

Depth of penetration in arc welding is affected by polarity, current, and current density. Penetration is increased by welding electrode positive. In GMAW and FCAW-G, the depth of penetration is also affected by the choice of shielding gas. WPSs for any process designed for vertical-up progression generally have much deeper penetration than the same process operated vertical-down. Only vertical-up welding is allowed by the code, unless qualified by tests and allowed by the Engineer.

All PJP V and bevel groove welds are subject to incomplete fusion at the root. The amount of incomplete fusion may vary, depending on welding conditions. Assembled with zero root opening, as the included angle of these groove welds decreases, the expected size of the fusion defect at the root increases. PJP details for V- and bevel-grooves assume a depth of penetration that is 3 mm [1/8 in] greater than the required weld size whenever the included groove angle will be less than 60°, unless welded with SAW.

When nonstandard PJP groove weld details are proposed by the Contractor, the Engineer should require evidence by testing that the required weld sizes will be routinely produced by the selected WPS. Macroetched sections can be used to demonstrate that the required penetration and fusion at the weld root can be routinely achieved using the given WPS (see 7.7.5).

C-4.3.1.4 Flare groove welds, a form of PJP groove weld, are not used in bridge construction because the curved groove configuration provides poor access for welding at the root. With poor root access, there is a greater chance of producing fusion discontinuities. In thick sections, a flare groove is uneconomical and impractical.

C-4.3.2.2 The provision for minimum fillet weld length establishes good weld design proportions. The minimum length is based on the minimum required for the fillet welds to effectively and reliably transfer loads. It also ensures that the welding arc is established long enough to produce sound welds and minimizes excessive hardening of the HAZ. This length requirement is tied to limitations on minimum groove and fillet weld sizes (see Tables 4.1 and 4.2).

C-4.3.3 Plug and Slot Welds. Plug and slot welds completely fuse the interface between adjacent parts within the area described by the hole or slot. Plug and slot welds should not be confused with fillet welds within a hole or slot. These are different types of welds, made by different procedures, and may have significantly different effective areas or sizes for a given hole or slot. Plug and slot welds should only be used for transmitting shear stresses.

There is a higher risk of discontinuities in plug and slot welds when compared with fillet welds. Plug and slot welds are extremely susceptible to slag inclusions and fusion discontinuities that can lead to fatigue cracks. Plug and slot welds should be avoided, and are prohibited in members subject to tension and reversal of stress [see 4.14(6)]. The risk of cracking can be reduced through special techniques, but plug and slot welds are inspected by RT or UT.

Often, high-strength bolts can perform the same design function as plug and slot welds with less adverse effect on fatigue life.

C-4.3.4 Welds in corner and T-joints are required to have reinforcing fillet welds where allowed by the geometry of the connected parts. In the calculation of weld size, PJP groove welds are given credit for the reinforcing fillet welds, but CJP groove welds are not given credit unless undermatched weld metal is used. The reason for this disparity is that the design cannot give extra credit for welds that are built-up to be stronger than the parts they join.

Part B
Structural Details

C-4.4 General

Because bridges are cyclically loaded structures, fatigue is an important design consideration. Fatigue is the result of repeated local plastic (inelastic) deformation. With enough cycles of such deformation, fatigue cracks can initiate and propagate. In some cases, stresses resulting from applied loads are elastic in a global sense, but localized areas may exist where the stresses concentrate or combine with internal stresses and exceed the yield strength of the metal. In welded construction, two factors can cause this to occur: stress concentrations and residual stresses.

Stress concentrations can occur due to geometric changes in a member and discontinuities in the base metal or weldment. There are many examples of geometric changes, some of which include changes in width and/or thickness of flange plates, welded cover plates and even reinforcement of a groove weld joining plates of similar sizes. Discontinuities can include laminations and nicks as well as cracks, porosity, incomplete fusion, and slag inclusions in welds. In some cases, the orientation of an imperfection can determine how severely it affects the member. This is why base metal laminations parallel to the direction of applied stress are acceptable within certain limitations.

Residual stresses also affect fatigue performance. Residual stresses exist in any welded structure due to shrinkage during cooling of the weld. This can be a particular concern in welding highly restrained members. Even though the stress resulting from applied loads to a welded member may be within the elastic range, the added effect of the residual stresses may result in an inelastic level at the welds.

AASHTO design specifications require that both the static strength and the fatigue strength be considered in design. The allowable fatigue stress ranges are based on full scale testing of as-welded components that replicate typical bridge details. These allowable stress ranges have incorporated the effects of geometric stress concentrations, allowable discontinuities, and residual stresses. Welded connections and connection details are to comply with these design parameters.

C-4.5 Welded Filler Plates

C-4.5.1 Filler plates have a long history of use in bridges constructed with riveted and bolted joints. When filler plates are used to make welded connections in members subject to tension and reversal of stress, the fatigue life of the member may be reduced. A filler plate is part of a welded connection and shown on the design drawings. Filler plates are categorized into two groups, those less than 6 mm [1/4 in] thick and those 6 mm [1/4 in] thick or greater in thickness.

C-4.5.2 Filler plates less than 6 mm [1/4 in] thick are restricted to the area between the adjacent parts, not intruding into the weld area. These may be used to separate adjacent parts and to provide backing by welding over the edge of the filler plate, just as root openings are spanned by welding against steel backing in web-to-flange and similar connections. Because small filler plates simply displace parts and carry no stress, the weld size is increased to compensate for the thickness of these filler plates and designed to carry the complete load.

C-4.5.3 When filler plates are 6 mm [1/4 in] or greater in thickness, the strength is developed by the welds on the perimeter. Filler plates of this type are not treated like thin filler plates. When two adjacent parts, A and B, are joined by welding and the connection includes a thick filler plate, the weld between A and the filler plate fully develops the maximum load on the connection, and the weld between the filler plate and B does the same. In addition to carrying the direct stress applied to the members, the welds have sufficient capacity to provide for any eccentricity created by the placement of the filler plates in the space between connected parts.

C-4.6 PJP Groove Welds

Editions of the code prior to 2010 prohibited use of PJPs where the applied tensile stress is normal to the effective throat of the weld. Generally, such use of PJPs on dynamically loaded structures should be avoided due to fatigue concerns. However, it is not always possible to avoid such use of PJPs; for example, such joints are often used in rib to floor beam welds on closed rib orthotropic decks. Therefore, rather than prohibiting use of such joints in the *Bridge Welding Code*, it is more appropriate for designers to use them where needed and design the connection to be within the applicable stress range designers rely on the AASHTO bridge design specification for such design and not on the *Bridge Welding Code*.

PJP welds in butt, corner, or T-joints subjected to cyclic tensile stresses normal to the effective weld throat are a fatigue concern because fatigue cracks may initiate at the weld root and propagate into the weld joint. The fatigue performance of such joints is relatively poor, requiring design for a low stress range.

When the unwelded portion of a PJP groove weld is parallel to the applied stress, there is no stress concentration. Except for CJP groove welds, all longitudinal welds that join the web to the flange in bridge members have unwelded portions. This applies to both fillet and PJP groove welded joints. Fillet welded connections have an unwelded portion between the fillets on each side of the web. PJP groove welds have an unwelded portion between the roots of the welds. The unwelded portion of all welded joints, subject only to shear stress parallel to the effective weld throat, has little adverse effect on fatigue life. This statement assumes the welds are sound regardless of joint configuration.

The code does not restrict the use of PJP groove welds for corner and T-joints where the applied stress is limited to shear parallel with the weld axis. The code requires restraint to be provided for connections with PJP groove welds or fillet welds to avoid concentrating tensile stress at the weld root making the joint susceptible to fracture initiation. The design should include restraint by opposite side connections, the configuration of the assembly, or some other means.

Part C
Details of Welded Joints

C-4.7 Joint Qualification

C-4.7.1 Because these details have a long history of satisfactory use in welding and in service, the details of welded joints shown in Figures 4.4 and 4.5 are considered standard, and the joint designs are exempt from testing when SMAW, SAW, GMAW, and FCAW are performed in conformance with code requirements, and when an appropriate WPS is used. Their use requires conformance with 4.9 and 4.10 and the details of the welded joints shown in Figure 4.4 or 4.5.

The essentials of good weld joint design are as follows:

(1) Provide good access to all parts of the weld joint during welding to ensure that good penetration and fusion is possible, and

(2) The joint uses only the minimum amount of weld metal necessary to produce sound welds of the required strength, and

(3) The joint uses weld metal placed in a manner that minimizes angular distortion and residual stresses (see C-4.1.1 and C-4.1.2).

Although the standard joint details may be used to make sound welds, the availability of these joint details does not mean that no other joint details can produce acceptable results. Many nonstandard welded joint details acceptable for specific applications may be less costly to prepare and weld and may reduce distortion or the risk of lamellar tearing. Many standard joint details, because of concern about sufficient access for welding, require excessive weld metal. Joint details that have a radius at the root and a small included angle may be preferred over details that have a large included angle simply to provide access at the root. Roots of welds may be gouged and/or ground after fitting to provide the required root radius.

Joint details that do not conform to the details shown in Figures 4.4 and 4.5 are considered nonstandard, and qualified by test as described in 7.7. Test Plate C, Figure 7.3, is a generic representation of a plate used to qualify nonstandard joint details. The costs of such tests are borne by the Contractor. Testing and approval of nonstandard joint details may provide cost savings and/or avoid fabrication problems (distortion, restraint cracks, etc.). The Engineer should approve new and nonstandard joint details based on these tests that prove that the joint's configuration allows the production of sound welds. Acceptance should also take into account knowledge of welding conditions, visual inspection and NDT, that when performed in production, will give confidence in the required weld quality.

C-4.8 Details of Fillet Welds

Fillet welds joining perpendicular components are identical to root passes in groove welds where the included angle is 90°. If the access and orientation of the parts being joined is acceptable, welding may be done successfully using SMAW, SAW, GMAW, or FCAW WPSs.

C-4.8.1 There is a direct correlation between weld size and heat input. Insufficient heat input or too low a preheat temperature for the thickness of the steel to be welded can cause unacceptable hardening of the weld or HAZ due to the rapid cooling of small welds. Unacceptable hardening may contribute to embrittlement. Weld metal embrittlement is less common, especially in lower strength electrodes, because the filler metal generally has less carbon and therefore is less hardenable than the base metal.

Small fillet welds, particularly on thick, insufficiently preheated steel, are potential crack initiation sites. For this reason, small cosmetic welded repairs should be avoided. When repairs are essential, welding should be done in conformance with the provisions of an approved WPS that provides adequate preheat.

Small reinforcing fillet welds for corner or T-joints may be made integrally with the much larger groove welds or later as separate welds. Single-pass fillet welds not made as an integral part of much larger welds are to conform to the minimum size requirements of Table 4.1, with the preheat and interpass temperatures conforming to 6.2.

The maximum fillet weld size is based on the ability to make sound welds while protecting the edge of a relatively thin material that is to receive a fillet weld along its edge. The part edge is melted and sometimes destroyed by the concentrated heat of the welding arc. This is not necessarily an indication of poor workmanship. Without proper controls, a weld on a relatively thin edge that has been melted away may have less effective size than it appears, and the effective weld size cannot be reliably measured. The maximum fillet weld size provision protects the edge to enable the monitoring and inspection of the fillet weld leg and throat.

C-4.8.2 Fillet welds in holes or slots are considered the same as fillet welds along edges of surfaces. Fillet welded attachments may overlap, in the sense that they are on opposite sides of a given hole or slot. Fillet welds are not intended to intersect or pile-up on each other. The effective size of two fillet welds that overlap within a hole or slot is not necessarily the sum of the two throats, because it is limited to the plan area of the hole or slot.

C-4.8.3 Care is to be taken when welding skewed T-joints to ensure that the required weld size is obtained. Detail drawings, to scale, showing the required leg size and throat, are helpful to the welder and Inspector in providing the required weld size.

C-4.8.6 Boxing requirements are applicable to lap joints when fillet welds are used to support loads that produce a tension component transverse to the throat of the fillet weld. Applied out-of-plane tensile force has the effect of trying to pry the weld off the base metal, tearing from the end of the weld, initiating at the weld root. By boxing, the ends of the longitudinal weld are restrained from opening, protecting the weld from prying behavior. The concentration of stress at the ends of the fillet weld, where weld quality is generally poorest, is also reduced by carrying the weld around the corner of the joint. Because it restricts the flexibility of the connection, boxing may need to be limited where connection flexibility is assumed, such as double-angle connections welded to the supporting member.

C-4.8.7 Opposite Sides of Contact Plane. It is difficult to maintain weld quality across the plane of contact because it requires a welding position change and frequently creates notch defects and undercut where the weld crosses the part. A typical application for this situation is the attachment of a cover plate that is wider than the flange as shown in Figure 4.6, or intersecting cross-frame members.

C-4.9 Details of Plug and Slot Welds

C-4.9.1.1 The techniques of welding plug and slot welds are substantially different than the techniques that would be used to weld WPS qualification test plates. However, plug and slot welds are not typically used for important welds to carry high stresses, and therefore procedure qualification requirements are normally waived.

C-4.9.2 The minimum diameter limitation provides access to make good quality welds with adequate fusion. The maximum diameter maintains a reasonable size of hole that may otherwise substantially reduce the net section of the part being joined.

C-4.9.7 This subclause contains a number of provisions for making plug and slot welds. Plug and slot welds have a high incidence of weld discontinuities when made by the methods described in 6.23 and 6.24. For this reason, 6.25 was added to the code, but does not guarantee that sound plug and slot welds will be produced. Plug and slot welding are prohibited on tension and reversal members [see 4.14(6)]. Plug and slot welding should be avoided whenever possible. High strength bolts can also be used to transmit shear and to keep adjacent plies of compression members from separating or buckling.

Designs that require parallel plies of material to be joined together by plug or slot welding are seldom used in modern bridge construction due to inefficient use of weld metal, the high incidence of weld discontinuities, and the susceptibility to crack initiation and propagation.

C-4.10 Lap Joints

C-4.10.1 Minimum Lap. A minimum lap of five times the thickness of the thinner part of the joint is necessary to avoid unacceptable rotation of the joint. The eccentric force tends to cause the plates to bend between the welds. As the lap becomes longer, the bending tendency is reduced. Lap joints with a single transverse fillet weld tend to open and apply a tearing action at the root of the weld. These joints are rarely used in bridge construction.

C-4.10.2 Longitudinal Fillet Welds. For longitudinal fillet welds used alone in a lap joint, the code requires, because of shear lag, that the length of each weld be at least equal to the width between the lines of weld. When the distance between the longitudinal lines of fillet welds becomes large, and buckling or separation of the parts becomes possible, then plug welds, slot welds, or some other means are used to prevent separation or buckling. Because of the difficulty of achieving adequate weld quality in plug and slot welds, plug and slot welds should be avoided when connecting cover plates or when making welded lap splices. When lap splices in tension members are required, the best method of connection is generally with high strength bolts (see 4.10.4).

C-4.11 Corner and T-Joints

C-4.11.1 Weld Arrangement. When applied loads may bend a corner or T-joint about its longitudinal axis, the weld is either a complete joint penetration (CJP) weld or double-sided fillet or double-sided partial joint penetration (PJP) groove welds on each side of the joint so that tensile stresses will not be concentrated at an unwelded, root portion of the joint. All corner and T-joints, where geometry allows, are required to have reinforcing fillets to improve the flow of stress and to mitigate the unavoidable stress concentrations present. When applied loads perpendicular to the weld axis tend to induce compressive stress on the weld root, and corrosion and strength considerations are satisfied, it may not be necessary to weld both sides.

C-4.11.2 Longitudinally Stressed Welds. Fillet welds provide the least expensive weld detail when applied shear stresses require fillet throat of about 18 mm [11/16 in] or less. Very large fillet welds should be avoided because they require excessive weld metal. As a general rule of thumb, when the required fillet weld size approaches 25 mm [1 in], the use of PJP groove welds with reinforcing fillets should be considered. Because of the method of calculating effective weld size (throat), PJP groove welds provide higher allowable shear capacity per pound of weld metal.

CJP groove welds are required only when shear or compressive stresses are unusually high, or when there is an applied tensile stress transverse to the effective weld throat. The provisions of this subclause allow bridge designers to use fillet welds and PJP groove welds when feasible and economical. Specifying CJP groove welds where not essential may increase cost, member distortion and residual stresses, and can lead to excessive amounts of repair welding.

C-4.12 CJP Groove Welds

C-4.12.1 Dimensional Tolerances. When the standard joints of Figure 4.4 are being detailed, they may be adjusted using the "As Detailed Tolerances" provided in Figure 4.4. When being assembled (fit-up) for welding, the joint may vary from the details shown on the approved shop drawings within the limits of the "As Fit-Up Tolerances" provided in Figure 4.4 for standard joints, or 5.3.4 and Figure 5.2 for other groove welded joints. The fit-up provisions of Figure 4.4 are derived from 5.3.4.

J- or U-grooves may be prepared before or after assembly, or after welding of the first side of a two-sided weld. Second side joint preparation made by gouging or grinding the root after welding the first side removes discontinuities in the root of the first weld and helps to ensure weld soundness. Unless the WPS is qualified per 7.7.5, CJP groove welds made without steel backing, except the B-L1-S standard detail, are backgouged to sound weld metal and ground to remove carbon arc gouging residue (carbon, copper, slag) before welding the second side. The backgouging may be used to produce the second side joint preparation. Joint preparation by gouging after the joint is assembled, but prior to welding, also helps ensure the accuracy of the joint alignment.

For thicker materials, the most economic CJP groove weld joint preparations are often J- and U-groove preparations, based on lower weld volume. These joints provide the best access for welding at the root and use the least amount of weld metal. However, J- and U-groove preparations are rarely used in shops prior to assembly because of assumed high costs since, prior to assembly, these joints can only be produced by machining. These difficulties may be overcome by modifying the thermal cut preparation of the top of the joint during initial preparation, then completing the joint preparation after assembly by air carbon arc gouging to produce the required root radius. Automatic machines are available that produce high quality joint preparations at reasonable cost.

C-4.12.2 Corner Joints (see Figure C-4.1). When one only considers access for fusion between weld metal and base metal, whichever plate is beveled during preparation of the weld joint is insignificant. However, since lamellar tearing is potentially a serious problem in corner and T-joints where shrinkage stresses pull on the base metal in the short transverse or "Z" direction, efforts should be made to minimize the potential for tearing. Shrinkage stresses have less adverse effects on plates stressed in the longitudinal direction (parallel to the rolling direction). There is little adverse effect when plates are stressed transverse to the rolling direction. However, stresses in the short-transverse, or "Z" direction, especially when the plate has nonmetallic inclusions, may cause lamellar tearing. Corner joints are particularly susceptible because one plate is stressed at its end or edge where there is no possibility to redistribute the stress, therefore the bevel should be made on the plate that will be subjected to the "Z" stress. This procedure spreads the shrinkage stresses from the surface toward the center of the plate or shape, and reduces the potential for tearing. Controlling weld volume, limiting weld metal yield stress, increasing preheats, using PWHT, and the use of controlled sulfur inclusion steels reduces the risk of lamellar tearing. Not all methods are needed for every application.

Plates may be ordered with improved through-thickness properties. They are produced with reduced sulfur content and controlled sulfur morphology, such that the sulfur that remains is not flattened by rolling to produce planar discontinuities parallel to the rolled surface. Such plates are available at increased material cost, and specified in the contract documents if required.

C-4.13 PJP Groove Welds

PJP groove welds are prohibited in any application where tensile stress may be imposed by live or dead loads normal to the weld throat. There is no code restriction on the use of PJP groove welds oriented parallel to the applied stress (see C-4.6).

PJP groove welds may be used to carry shear stresses in bridge members regardless of the type (tension or compression) or intensity of the stress in the member. The effective groove weld size is to be sufficient to carry the applied stress without exceeding design allowable stresses. Longitudinal PJP welds in corner and T-joints may be used to join web to flange in I-shaped and box-shaped members.

C-4.13.2 Minimum Effective Weld Size. The minimum weld size is based on the need for adequate heat input to slow cooling rates, and to provide a lower bound level of strength to assure that handling stresses during fabrication can be accommodated.

C-4.13.3 Corner Joints. See 4.12.2.

C-4.14 Prohibited Types of Joints and Welds

This subclause prohibits welded joint details and welding conditions that may leave an unwelded area or poor quality weld in a portion of the joint, resulting in stress concentrations that may initiate fatigue cracking.

(1) The code prohibits groove welds in butt joints not fully welded throughout their cross section except in compression members with finished-to-bear splices per 4.17.3. When tensile stress is applied normal to the unwelded portion of the joint, fatigue cracking may initiate.

(2) These joints are prohibited because without proper backing materials, it is more difficult to ensure complete fusion of the weld at the root, resulting in a high potential for reduced fatigue performance. Doublesided joints with backgouging, are allowed. It is also permissible to qualify the use of backing materials other than steel, providing the tests described in 7.12 are conducted.

(3) Permanent intermittent groove welds are prohibited because they concentrate residual and applied stress at the ends of the welds, and the concentration of stresses may initiate fatigue cracking.

(4) Permanent intermittent fillet welds are not allowed because they concentrate stress at the ends of the welds, and the concentration of stresses may initiate fatigue cracking. Each intermittent weld is similar to a Category E fatigue detail.

This restriction does not prohibit the use of intermittent fillet welds as tack welds to be welded over to complete a continuous weld.

The Engineer may allow the use of permanent intermittent fillet welds in specific applications such as the welding of members exposed only to very low design cyclic stresses, few cycles, or to ancillary items listed in 1.3.7. Corrosion, distortion, and secondary stresses should also be considered.

(5) Previous editions of this code restricted certain groove welds made with preparation on only one member to the horizontal position. Such groove types include bevel and J-preparations, as opposed to preparations where both members receive the treatment, such as V and U-grooves. This restriction was placed because of the general preference for avoiding welding against a vertical face whenever possible, and led to utilizing preferred V- and U-groove details in lieu of bevel and J-groove details when either option was possible, since in the flat, vertical, and overhead positions, it is generally considered easier to make a quality weld when both members are prepared to receive the weld metal. When welding in the horizontal position, the single member preparations are preferred, and thus allowed by previous codes.

This provision was changed because there are certain applications where flat position welding with single member preparations is preferred. The most notable example is for horizontal plates welded to flanges where the attachment functions as a transverse connection plate. Under the previous editions of the code, these welds either needed to be made with two member preparations (V- or U-groove details), requiring beveling of the main member (girder flange) for the length of the attachment; or, these welds were required to be made in the horizontal position. Horizontal groove welding is generally more difficult than flat position groove welding, and significant material handling is often required in order to accomplish this task. In many cases, the specific requirements of the code with respect to this application were overlooked and the joint, with one member prepared, was actually welded in the flat position.

To overcome this problem, the 2002 code provision was modified by changing 4.14, as well as adding Note I in the notes for Figures 4.4 and 4.5, allowing the use of these details in the flat position, but disallowing such weld details where V-groove and U-groove details are "practicable." This term incorporates two concepts: 1) possible or doable and 2) practical or generally accepted practice.

For example, routine web and flange butt joints made in the flat position are quite readily accomplished with V-groove or U-groove details, and this is routinely done, that is, it is practicable. However, welding a horizontal connection plate to a girder flange with a V- or U-groove preparation is possible, but does not pass the practical test, and thus would not be practicable.

Contained within the term "practicable" is an element of judgment, deliberately incorporated by the Bridge Welding Subcommittee to allow appropriate latitude to address the myriad of situations that could arise.

(6) Plug and slot welds are not allowed on members subject to tension and reversal of stress because of stress concentrations at the weld boundary. Plug and slot welds have a high incidence of fusion defects that act as stress concentrations, possibly causing crack initiation. Both the weld metal and the surrounding base metal have low allowable stress ranges for these reasons.

C-4.15 Combinations of Welds

The capacities of individual weld types can be added to determine the total capacity of a weld joint, with the sum not to exceed the strength of the weakest member being joined. Fillet welds that reinforce CJP groove welds are given no credit in design. They simply help to improve the flow of stress and minimize stress concentrations. The strength of fillet welds used to reinforce PJP groove welds may be taken into account when calculating the strength of a welded joint, provided the combined weld strength does not exceed the capacity of the connected material (see Annex A).

C-4.16 Welds in Combination with Rivets and Bolts

Bolts and rivets have traditionally been prohibited from sharing stress with welds in bridge design because most riveted and bolted joints do not fully share the load and may slip and cause the full load to be transferred to the weld. If joint slip happens only once and in one direction, it is possible that the weld could yield and then share the load with fasteners in bearing, as necessary. However, under conditions of stress reversal, once bolted or riveted joints slip, the "slip critical" bolted connection is lost. The AASHTO *Design Specifications* do allow bolted cover plate terminations to improve the welded cover plate's fatigue category. Such a detail is not considered load-sharing.

Unless required for strength, if bolts are removed after assembly, it is generally preferred that the exposed bolt holes should not be filled by welding. There is a considerable risk that discontinuities in the weld will lead to fatigue crack initiation (see 5.7.7 for welding techniques and limitations for filling bolt holes).

C-4.17 Connection Details

C-4.17.1.1 General. Eccentricity of members should be minimized whenever possible. When eccentricity is necessary due to the configuration in the design of members and connections, provision for the additional stresses created by the eccentricity is necessary. Welds should be arranged, or diaphragms and other bracing members placed, so that tensile stresses are not concentrated at ends of welds or at unwelded portions of welded joints.

C-4.17.1.3 Symmetry. Symmetric welds for symmetric members are desirable but may not always be possible where connections or other attachments are made to the primary member. Under such situations, allowance is needed for the resulting eccentricity.

C-4.17.2 Connections or Splices—Tension and Compression Members. Connections or splices in bridge members that will transmit tensile and compressive stresses are required to be made using CJP groove welds or fillet welds with external splice plates. CJP groove welds in butt joints have the best fatigue strength because there is no unwelded portion of the joint to cause stress concentration.

C-4.17.3 Connection or Splices in Compression Members with Finished-to-Bear Joints. Finished-to-bear surfaces rarely mate perfectly. Per 5.3.2.2, the contract documents may specify the tolerances for noncontact surfaces. When a mill-to-bear condition is specified for a column base plate or against a bearing assembly, welds accommodate localized plastic strains if these noncontact surfaces close under subsequent loadings. AISC and AREMA also specify fit-up tolerances for such joints that may be adopted for some situations.

This subclause does not apply to milled ends of bearing stiffeners prepared for full contact or components within a bearing assembly.

C-4.17.4 Connections of Components of Built-Up Members. A large portion of welding in bridge construction consists of longitudinal welds used to join member components, such as webs and flanges, to make them act in unison. The applied stress on the welds is shear on the effective weld throat, even though the member may be axially loaded or subject to bending. Generally, minimum weld sizes govern such connections. Intermittent welds are not allowed because of their poor fatigue performance.

C-4.17.5 Transition of Thicknesses or Widths at Butt Joints. When there is a transition in thickness or width, there is a concentration of stresses. Extensive fatigue testing and the service history of thousands of welded bridges has shown that transitions in weld and base metal surfaces that provide a smooth transition of the surfaces or edges, or both, at a slope that does not exceed 1 on 2.5, ensures acceptable fatigue performance.

C-4.17.5.3 An abrupt change in width between tension members causes a stress concentration at the point of transitions. A gradual transition reduces this stress concentration. Either a tapered transition or a radiused transition accomplishes this reduction in stress concentration. For lower strength steels, a 1:2.5 width:length taper reduces the stress concentration to a level such that the allowable stress range is the same as a butt splice of equal width. For higher strength steels the radiused transition provides a slightly better performance than does the tapered transition. Accordingly, AASHTO design specifications allow a slightly higher allowable stress range for radiused transition versus tapered transition in these higher strength steels. The slightly higher allowable stress range rarely changes the bridge design, and it may be easier for the fabricator to supply the tapered transition. Thus, either transition detail is allowed, regardless of the strength level, but in all cases, the AASHTO allowable stress levels are not to be exceeded.

C-4.17.6.2 Splice Planes. Full cross-sectional splices in beams and girders are generally best made in a single plane. There is no strength or fatigue advantage to staggering the splice, and staggered splices are considerably more difficult and expensive. Locations may be based on requirements for changes in material thickness, or as necessary to accommodate lengths of steel available from the mill. Unnecessary flange and web splicing should be avoided.

Before the webs and flanges are assembled to form a beam or girder, components of the web or flange are joined by shop welding and the quality of the welds accepted (see 5.4.6). This provides the best access for welding, and keeps residual stresses to a minimum by reducing restraint. When assembly and welding are done in this manner, the longitudinal web-to-flange welds can be made by automatic welding procedures without interruption. Field splicing built-up sections requires access holes cut in the web. When flanges are spliced without backing, the access or cope hole in the web may need to be larger than one with backing. The hole provides access for welding, backgouging, and subsequent grinding of weld surfaces. Top or bottom access holes will also be subjected to applied tension and/or reversal of stress. Any notch in the weld or base metal at this location may initiate fatigue cracking. Thermal cut access holes may have a thin layer of untempered martensite that should be removed by grinding.

Many prefer to leave access holes open and have had good results in redundant members. A bridge member with an open access hole should have an allowable design stress range considerably lower than that allowed for Category B. Flange to web fillet welds terminating at access holes are essentially Category E or E' details. The filling of access holes requires skillful use of Engineer-approved procedures and should only be employed when holes cannot remain open. Installing an insert plate joined to the web and flange using CJP groove welds is very difficult due to access for backgouging, and weld defects at corners may be more detrimental than an open hole. The welds and base metal are at yield stress when the repair is complete, and there may be very high surface or internal stress concentrations at the completion of access hole filling. It is essential that the specified quality of access hole welding be verified by NDT. Welds in tension areas should meet the tension quality requirements of the code, and welds in compression areas should meet the compression requirements of the code.

C-Figures 4.4 and 4.5

CJP Groove Welds C-Figure 4.4

B-L1a, C-L1a, B-L1a-GF. These joint details are only suitable for groove welds in thin material. Because of limited access at the root and the possibility of fusion discontinuities at the root, caution should be used for welds carrying calculated stress.

B-L1b, B-L1b-GF, B-L1-S, B-L1a-S. When a square groove is made without steel backing, lack of fusion at the root pass is common. Note 3 requires welds made without steel backing to be backgouged to sound metal to remove fusion discontinuities in the root of the first side weld before welding the second side. When using SAW with material 10 mm [3/8 in] or under in thickness, an exception to this backgouging requirement is made. This detail has been commonly used for bridge girder web splices.

TC-L1b, TC-L1-GF, TC-L1-S. This group of joints is similar to the above group beginning with B-L1b. Backgouging is required for all joints, including the SAW joint limited to 10 mm [3/8 in] in thickness.

B-U2, B-U2-GF, B-L2c-S. Because of the wide groove angle, these joint details use excessive weld metal in thick sections and increase angular distortion. Backgouging is required on the second side.

Whenever the second side weld is not larger than the first, there may be insufficient weld shrinkage to counteract the angular distortion produced by the first weld (see C-4.1.2).

B-U2a, B-U2a-GF, B-L2a-S, B-U2-S. These details are suitable for all thicknesses. These are particularly useful in avoiding out-of-position welding and are commonly used for field welding and repair. As weld sizes increase, these joints become less and less economical. Root openings and groove angles should be adjusted to require the minimum weld volume. Large included angles increase distortion in weld joints that join thick sections. The B-L2a-S weld detail is limited to a maximum thickness of 50 mm [2 in], because as thickness increases, the angular distortion may become excessive. Access for the SAW equipment is also limited when the thickness exceeds 50 mm [2 in]. This is overcome by increasing the root opening to 16 mm [5/8 in].

C-U2, C-U2-GF, C-U2b-S. Because of the wide groove angle, these joint details use excessive weld metal in thick sections and increase angular distortion. Backgouging is required on the second side.

C-U2a, C-U2a-GF, C-L2a-S, C-U2-S. These details are suitable for all thicknesses. These are particularly useful in avoiding out-of-position welding and are commonly used for field welding and repair. As weld sizes increase, these joints become less and less economical. Root openings and groove angles should be adjusted to require the minimum weld volume. Large included angles increase distortion in weld joints that join thick sections. The B-L2a-S weld detail is limited to a maximum thickness of 50 mm [2 in], because as thickness increases, the angular distortion may become excessive. Access for the SAW equipment is also limited when the thickness exceeds 50 mm [2 in]. This is overcome by increasing the root opening to 16 mm [5/8 in].

B-U3b, B-U3-GF, B-U3c-S. As a two-sided weld, it may be detailed to minimize angular distortion by making adjustments to the location of the root face or minor adjustments to the groove angle. For thicker sections, the weld volume is still minimal compared to a single-sided weld. It is best when assembled with a very small, or zero, root opening, with sufficient root face to support the welding heat of the root pass. When the root opening is the maximum allowed and/or the root face is small or nonexistent, making a sound weld without burning through is difficult. The root face should be adequate to absorb the welding heat without burning through, since the weld will be backgouged.

B-U4a, B-U4a-GF. In previous editions of this code, the welding position for this joint has been restricted to the horizontal position. This restriction was applied because, in general, single-V-groove details (such as B-U2a) are preferred, and is certainly applicable for flat position welding. In the flat position, B-U4a with the vertical edge on one side of the joint is more prone to fusion defects than a single-V-joint with two inclined surfaces. B-U4a is identical in cross-sectional configuration to the code acceptable TC-U4c. The TC-U4c series of joints does not have the similar restriction to the horizontal position only, even though it has the same geometry as the B-U4a detail. The lack of the restriction on the TC-U4c joint is for practical reasons: In T- and corner-joints, it is impractical to bevel both members.

In most situations, a detail such as a B-U2a will be practical and preferred over the use of a B-U4a detail. However, there are a variety of situations where a B-U2a is impractical and a B-U4a is permitted by the code. The primary example of this is for a horizontal transverse connection plate, welded to the edge of the girder flange. Under such conditions, it is undesirable to bevel the edge of the main girder flange. It is also impractical to require that such welds be made in the horizontal position if only the connection plate is beveled. Therefore, the code was changed to permit welding of a B-U4a detail in the flat position, but this option is only extended when it is not "practicable" to use U- or V-groove details (see Note I).

TC-U4c, TC-U4c-GF, TC-U4a-S. Welds in T-joints should be made from one side with steel backing only when a CJP groove weld is required and when there is no access to the backside of the weld for backgouging and backwelding. Welds of this type use excessive weld metal when compared to balanced two-sided welds. Angular distortion may become excessive when the parts are free to move, and high residual stresses may be created when the parts are not free to move.

CJP corner welds should be made by beveling the plate that will be stressed in the "Z" direction, as noted in the figure on the right. This will help avoid lamellar tearing.

B-U4b, B-U4b-GF. This butt joint is restricted to welding in the horizontal position because of weld access, similar to B-U4a. Backgouged welds require less weld metal than similar welds made against backing. Weld quality is generally superior when backgouging is required because root pass discontinuities are removed. Note that the root face is not limited during fit-up. However, it is essential that there be sufficient root face to prevent burning through. Any remaining root face is removed by backgouging.

TC-U4b, TC-U4b-GF, TC-U4b-S. Welds in T-joints should be made from one side with steel backing only when a CJP groove weld is required and when there is no access to the backside of the weld for backgouging and backwelding. This detail is used when access is available from the backside for backgouging and backwelding. Angular distortion may become excessive when the parts are free to move, and high residual stresses may be created when the parts are not free to move.

Backgouged welds require less weld metal than similar welds made against backing. Weld quality is generally superior when backgouging is required because root pass discontinuities are removed. The root face is not limited during fit-up. However, it is essential that there be sufficient root face to prevent burning through. Any excess root face is removed by backgouging.

CJP corner welds should be made by beveling the plate that will be stressed in the "Z" direction, as noted in the figure on the right. This will help avoid lamellar tearing.

B-U5a, B-U5-GF. This type of joint preparation is more economical in the use of weld metal than joints requiring steel backing. Note that the lower plate may be beveled up to 15°. Like all other bevel or J-groove welds, this joint preparation is only allowed to be used in the horizontal position. The included angle is only 45°, even though the root opening may be zero. Other weld details with similar access require 60°. Backgouging to sound metal before welding the second side helps ensure weld soundness and makes large included angles for root access unnecessary.

TC-U5b, TC-U5-GF, TC-U5-S. This is similar to the BU5 joint detail above. The 60° included angle for SAW is to limit the shape of the weld nugget and prevent center bead cracking (see Figure 6.1). SAW does not need more access than other processes.

B-U6, C-U6, B-U7, B-U8, TC-U8, B-U9, TC-U9 and Variations. All of these joints use J- and U-grooves. These joints provide the best access for welding and use the least amount of weld metal when thick sections are to be welded. Angular distortion is minimized because of the narrow groove angles required, particularly the 20° grooves. Such narrow groove angles may be utilized because of the rounded, wide root that offers good access. In practice, they are rarely used except in thick joints because of the cost of preparing the J- or U-groove. These joints with rounded roots provide an effective root opening of 12 mm [1/2 in] in U-grooves and 10 mm [3/8 in] in J-grooves because of the specified root radius.

These CJP groove welds are backgouged before welding the second side, resulting in a U-groove at the root. V or single bevel groove preparation is generally done by thermal cutting, which is less expensive machining or grinding. Bevel or V-joints modified to produce a rounded root may justify the time and expense of qualification testing if sound welds are produced at significantly reduced cost.

The root face specified for these joints is expected to prevent melting through. A generous root face can be helpful to prevent burning through and is no detriment to weld soundness since the weld is required to be backgouged to sound weld metal before welding the second side. In most cases the code states that the fit-up tolerance on root face dimension is unlimited. Melting through at the root and loss of support for the arc may cause serious discontinuities needing repair before welding can continue.

PJP Groove Welds C-Figure 4.5

Most commentary on the CJP details of welded joints, including access for welding, economy, distortion, susceptibility to lamellar tearing, etc., also applies to PJP groove weld details. The primary difference between PJP and CJP groove welds is that an unfused area exists at the root of the PJP groove weld or welds. There is no backgouging. The amount of lack of fusion at the root of the joint preparation will depend on the root opening, the groove angle, and the presence or absence of a root radius. The design and preparation of shop drawings should take into account the difference between the depth of the groove preparation and the effective weld size.

C-Notes for Figures 4.4 and 4.5

Note a. Each WPS has slightly different requirements for access during welding. In SMAW, the electrode diameter controls. In FCAW-G and GMAW, the diameter of the gas cup controls. The position of welding also has some effect on access requirements. GMAW and FCAW are capable of deeper penetration, depending on welding variables and shielding gas, if any.

SAW is somewhat different because it is capable of much deeper penetration than most other processes, particularly when operated electrode positive. SAW is also different from the other procedures because it is not an open arc process, in that the SAW arc is not seen during welding. Electrode placement cannot be controlled by visual monitoring as is done in other arc welding processes.

These considerations become very important in large nonstandard joints but are not a factor in the details shown in Figures 4.4 and 4.5.

Note f. A double-groove weld joint that places more than 75% of the weld throat on one side of the joint has higher residual stresses and distortion from shrinkage of the greater weld volume and weld width.

Double-groove welds that have each side welded completely, without alternating sides, may use uneven groove depths to balance distortion. Generally, the first side welded should have approximately one-third of the total groove depth, and the second side welded should have approximately two-thirds the total groove depth. The smaller first side weld is unrestrained from shrinkage and angular distortion, whereas the second weld is restrained by the first weld, and therefore needs additional weld volume to return the joint to approximately its original position.

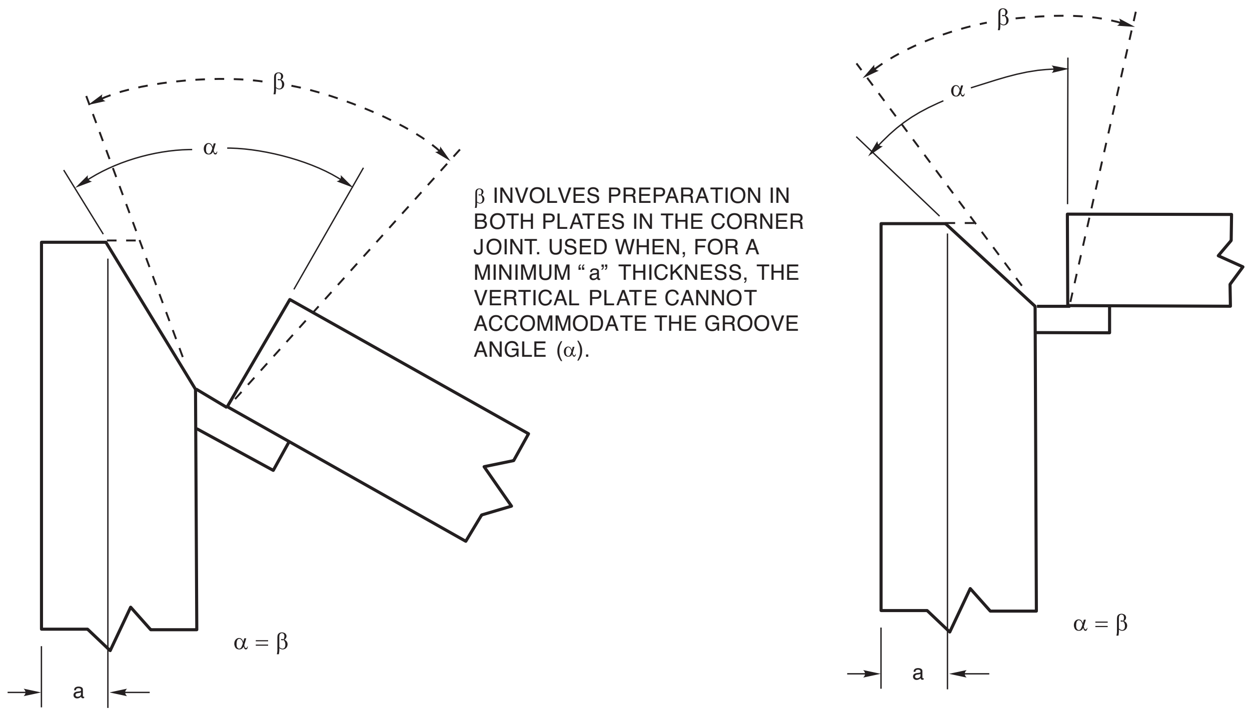


Figure C-4.1—Details of Alternative Groove Preparations for Corner Joints (see 4.12.2 and 4.13.3)

C-5 Workmanship

C-5.1 General Requirements

C-5.1.1 This introductory provision emphasizes the importance of conformance with all workmanship requirements. When contract documents specify that construction is to conform with the requirements of the *Bridge Welding Code*, it means all applicable provisions, not just Clause 5.

C-5.1.2 The equipment should be proper for the job and in proper working order so that qualified people can do acceptable work. It is essential that gauges and controls on welding equipment function properly so that the WPSs established can be duplicated accurately. Equipment calibration is required on a regular basis (see 6.28). Personnel other than qualified welding personnel are allowed to use thermal cutting equipment.

C-5.1.3 Welding is not to be done under conditions that may lead to poor weld quality.

Ambient conditions are the conditions that prevail in the immediate area where welds are to be made. It is assumed that welding personnel cannot consistently produce acceptable results when working in an environment where the temperature is lower than –20°C [0°F]. Should the Contractor build a shelter to protect the welding area, the "ambient conditions" are within the shelter near the weld. If the structure or shelter provides an environment at –20°C [0°F] or above, adequate light and protection from wind, this prohibition is not applicable. The environmental conditions inside the structure or shelter do not alter the preheat or interpass temperature requirements for base metals described elsewhere in the code. Conditions outside the shelter are of no consequence when determining whether or not welding may be performed. Low temperatures may also make it difficult for machines to function properly.

Any source of moisture such as condensation, dew, rain, or snow is a source of hydrogen during welding and is to be eliminated. Moisture increases the risk of hydrogen-induced cracking and other weld discontinuities.

High winds blow away shielding gases, leaving an exposed arc free to pick up atmospheric gases. This contributes to porosity as well as higher nitrogen levels that reduce weld toughness. Although high wind velocity is not defined in the code for SMAW, FCAW-S, SAW, and ESW, it is generally considered to be the wind speed that visibly blows the puddle, which typically occurs around 40 km/hr [25 miles/hr]. High winds also make it difficult for welders to do their work properly. The gas shielded arc welding processes, GMAW, FCAW-G, and EGW, require more protection from the wind than the other welding processes, and are subjected to a wind speed limitation of 8 km/hr [5 miles/hr] (see 6.13.3).

C-5.1.4 The approved shop drawings show welds of specific size and length. This is done to provide the required strength. Completed welds should be at least as large as shown on the drawings, unless otherwise approved by the Engineer. Fillet welds may have a slight underrun in size as provided in 8.26.1.7. This later provision is intended to provide a reasonable tolerance on workmanship and to avoid unnecessary repair by welding, which could cause more harm than good. Small localized underruns in size will not significantly impair strength or have a significantly faster cooling rate. Small, largely cosmetic weld repairs may cause additional residual stresses, unacceptable hardening, inclusions, or other detrimental effects. Therefore, undersized welds may be better left unrepaired than repaired with small welds to build out the weld to full size.

Either or both legs of fillet welds may be oversized without correction, provided the excess does not interfere with satisfactory end use of a member. Attempts to remove excess material from oversized welds, with otherwise acceptable profile, serve no purpose. Adequacy of throat dimension and conformance to the weld profile requirements of 5.6 should be the only acceptance criteria.

The location of welds is important for many reasons including strength and fatigue performance. Welds should not be moved or rearranged from the design location shown on the plans and detailed on the shop drawings without the approval of the Engineer.

C-5.1.5 Temporary and unauthorized welds are a potential initiation point for hydrogen and fatigue cracks. Welding is only acceptable where shown on the approved drawings and in conformance with code requirements.

Repair welds to base metal under the terms of AASHTO M 160M [ASTM A6] are allowed. However, it may be difficult to verify that the repair by welding of plates and shapes at the mill has been performed under conditions that conform to code requirements. For fracture critical members as provided in Clause 14, only the fabricator may perform welded repairs to the base metal.

C-5.2 Preparation of Base Metal

Poor quality of metal surfaces or edges can adversely affect the quality of welds made against those surfaces or edges.

C-5.2.1 General. For quality welds, base metal cleanliness is important. However, it is neither required nor necessary for base metal to be perfectly clean before welds are made. It is difficult both to establish quantifiable limits of cleanliness and to measure to those limits; therefore, this provision uses the practical standard of the resultant weld quality. If the base metal is sufficiently clean so as to facilitate a weld to be made that meets the requirements of this code, it is clean enough. If the resultant welds do not meet the weld quality requirements of this code, cleaner base metal may be required.

C-5.2.2 Mill-Induced Surface Defects. The base metal to which welds are attached must be sufficiently sound so as to not affect the strength of the connection. Base metal defects may be repaired prior to the deposition of the prescribed weld. This subclause does not limit base metal repairs by welding.

C-5.2.3 Scale and Rust. Excessive rust or scale can negatively affect weld quality. The code permits welding on surfaces that contain mill scale, providing both: (a) the mill scale remains intact after wire brushing and (b) the resultant weld quality is not adversely affected.

Web-to-flange welds are frequently minimum size fillet welds deposited at relatively high speeds; therefore these welds could exhibit piping porosity if welded over the heavy mill scale often found on thick flange plates. Therefore, web-to-flange welds in girders have the mandatory requirement to completely remove all mill scale. Similarly, welds subject to tensile stress at the weld root are more sensitive to internal discontinuities, so scale is also prohibited.

See C-5.2.1.

C-5.2.4 Foreign materials. This subclause prohibits volumetric (three dimensional) quantities of contaminants from being left in place on the surface to be welded and adjacent areas. Surfaces contaminated by the materials listed in 5.2.4.1 must be cleaned, such as by wiping prior to welding. Special consideration should be given to the removal of surface contaminants containing hydrocarbons or condensed moisture as the hydrogen released into the molten weld pool can cause serious weld imperfections, e.g., cracking. The cleaning operations, which may involve just wiping, need not remove all foreign contaminants nor do they require the use of solvents; welding through thin layers of remaining contaminants is acceptable, unless they degrade the weld quality requirements of this code resulting in unacceptable welds.

C-5.2.5 The effect of thermal cutting on steel is complex. Thermal cutting is generally done by either oxygen cutting or plasma cutting. Performance of steel bridge members constructed with plates or shapes with thermal cut edges may be affected by both the mechanical and metallurgical properties of the cut surfaces that are subject to tensile stress. Maximum surface roughness and freedom from unrepaired notches are specified to avoid stress concentrations.

Both plasma and oxygen cutting can produce acceptable cut surfaces if the equipment is properly operated and guided. Free-hand cutting should not normally be allowed because it is difficult to achieve uniform, regular cut surfaces with this technique. However, free-hand cutting is sometimes necessary. The quality of the thermal cut surface is expected to conform to the requirements of 5.2.5. When the Engineer approves free-hand cutting (without a mechanical guide), the cut surfaces still need to conform to the requirements of 5.2.5 and 5.2.7. Thermal cutting needs to be done with great care, avoiding any damage to the adjacent steel. Irregularities in the cut surface may be corrected by grinding, or by welding followed by grinding as specified in 5.2.5.1, 5.2.5.2, and 5.2.5.3.

A maximum surface roughness of 25 µm [1000 µin] is specified for steel up to 100 mm [4 in] thick. 50 µm [2000 µin] is specified for thicknesses over 100 mm to 200 mm [4 in to 8 in] inclusive and for ends of members not subject to calculated stress. A 25 µm [1000 µin] surface roughness represents a 0.025 mm [0.001 in] deviation above or below a theoretical plane. Deviations of these dimensions generally do not cause significant stress concentrations unless extremely sharp. Inspectors are not expected to measure surface roughness directly, so visual and tactile comparison with a surface roughness gauge is acceptable. AWS C4.1-G, *Oxygen Cutting Surface Roughness Gauge*, may be used as a guide for evaluating surface roughness of these edges. For materials up to and including 100 mm [4 in] thick, use Sample No. 3, and for materials over 100 mm [4 in] up to 200 mm [8 in] thick, use Sample No. 2.

Occasional notches and gouges in thermal cut edges that will not be weld joint fusion faces may be addressed by fairing-in the depression to adjacent surfaces on a 1:10 slope, provided at least 98% of the nominal section remains. Small repairs by grinding are preferred to welded repairs, which have the possibility of introducing new discontinuities. The number of repairs allowed in one region is not limited, but if repeated attempts to repair are required, the technique used should be investigated.

C-5.2.5.1 Notches and gouges occur in oxygen and other thermal cut edges for two primary reasons: (1) the cutting unit is not guided or operated correctly, or (2) the steel contains inclusions that interfere with cutting by deflecting the cutting jet. When there are discontinuities in thermal cut edges solely as a result of the cutting procedure, they may be repaired by welding as specified. When there are discontinuities in thermal cut edges because the steel has inclusions, repairs cannot be made until the extent of the inclusion and the possible effect of the inclusion has been determined. There is no limitation to the depth of gouge that may be repaired by welding when the repair WPS is approved by the Engineer. When the member will be subject to tension or reversal of stress, repair weld quality is verified by test as required by 5.2.5.3. Compression member repair welding generally requires only visual inspection because fatigue crack growth is limited in such members.

C-5.2.5.2 Because of their tendency to reach unacceptable hardness with rapid cooling, welded repairs to notches and gouges in thermal cut edges in 620 MPa to 690 MPa [90 ksi to 100 ksi] yield strength steels are limited to only those edges that will be included within a groove welded joint, or the faying surface element in a fillet welded T-joint. The code prohibits welded repairs for notches and gouges in thermal cut edges other than these specific situations. For repair of unwelded portions and other types of welded joints, only fairing out is allowed unless the Engineer approves a welded repair.

All repairs by welding for these steels are to be done with the approval of the Engineer and follow the requirements of an approved WPS. Stringer bead techniques should be used for all weld repairs except those made by welding in the vertical position. Welding in the vertical position, when approved, should consider the higher welding heat input associated with that procedure. Total heat input should not exceed the manufacturer's recommendations. The soundness of repair welds is verified by NDT as described in 5.2.5.3.

The Engineer may approve repair by welding, regardless of the depth of gouge, provided there is evidence that the steel is sound and that the proposed repair WPS will produce acceptable results.

C-5.2.5.3 Welded repairs to thermal cut edges in members subject to tension or reversal of stress are tested by both UT and MT because of the possibility that fatigue cracks might initiate from weld discontinuities in the repair. These two NDT methods were chosen because repair welds are generally expected to be shallow and because RT does not give good results near an edge without the use of edge blocks. Visual inspection of repairs to compression members is satisfactory, unless otherwise specified or required by the Engineer.

C-5.2.6 This provision addresses the significance of visually apparent discontinuities in cut edges. These edges are generally thermal cut edges but may also include sheared, machined, and air carbon arc gouged edges. Most discontinuities in edges of base metal are parallel to the rolled surface. There may be several planes of discontinuities throughout the thickness of the material.

Minimizing repair welding is desirable to avoid residual stresses and fatigue issues, but shallow repairs may not be adequate when tensile stresses are applied through-thickness in the material.

A working knowledge of steelmaking aids the Engineer in understanding the origin of discontinuities found in steel products. Most discontinuities are the result of nonmetallic inclusions, such as manganese sulfides and silicates, or are the remnants of voids left by escaping gases that are flattened out during rolling. Laminations and inclusions are generally more prevalent in thicker sections.

In ingot cast steels, there is a shrinkage cavity at the top of an ingot after solidification. The size of the cavity, called "pipe," depends on the method of casting and the effectiveness of "killing" the steel. Killing is a degassing process through the addition of aluminum or silicon. The top of the ingot is to be "cropped," cut off, and discarded. When there is insufficient cropping at the top of an ingot, major discontinuities may be found in the plates or shapes produced from that ingot. Plates ripped along the centerline are more likely to exhibit laminations along the edge. Many fabricators "nest" plates in odd quantities to ensure that "splitting" the plate along the centerline is avoided.

Today, most structural steels are produced through a process known as continuous casting. The use of ingots is eliminated, as steel in the molten state is tapped directly from ladles into casting units. The potential problem of "pipe" is eliminated. However, there is still the possibility of small inclusions in the steel from fluxes and other foreign elements within the steel, which is subsequently cast and rolled out in the section. Weathering steels seem to have more nonmetallic inclusions than other structural steels.

Most of these discontinuities have no bearing on the capacity of the steel to carry stress parallel or transverse to the rolling direction and do not adversely affect weldability. Inclusions and laminations can seriously impair the capacity of steel to carry stress in the short transverse or through-thickness "Z" direction.

C-5.2.6.1 Discontinuities found in thermal cut edges by visual inspection, or as a result of performing NDT, are investigated. Laminations may be discovered and mapped using longitudinal wave (straight beam) UT. Laminations are generally undetected by RT because they have no significant depth parallel to the inspecting radiation. The exception to this RT limitation is created when adjacent welds cause gases to expand out of a lamination, forming porosity that can be recorded by RT. However, what is detected is the porosity, not the lamination.

C-5.2.6.2 Table 5.1 summarizes the extent of investigation and repair needed, if any, based on the length of discontinuity in the cut edge and the depth of the discontinuity from the cut edge back into the steel. This includes all edges of steel shapes and plates, regardless of rolling direction and regardless of whether the edge is produced by thermal cutting, shearing, machining, or any other process. When the depth of discontinuity exceeds 3 mm [1/8 in] and grinding or other destructive methods for investigation are not desired, UT using longitudinal waves (straight beam) is very effective in detecting laminations.

C-5.2.6.3 Good base metal should not be removed unnecessarily. Shallow excavations made to discover the depth of discontinuities may not require repair by welding. Excessive metal removal reduces the net section of the plate or shape.

C-5.2.6.4 Unacceptable discontinuities that appear at the surface of as-rolled material, such as the edges of flanges in beams, are not addressed by Table 5.1. They are repaired as specified in the delivery requirements or the contract documents. The common specification for delivery requirements of steels listed in this code is ASTM A6/A6M.

C-5.2.6.5 Inspection of cut edges should be done early so that there is no unnecessary delay to construction. Edge discontinuities should be repaired and inspected before the material is incorporated into fabricated members. If a portion of the steel is found unacceptable and cannot be repaired, it needs to be replaced. In other cases, it may be desirable to put repaired plates in compression areas of the structure. This can often be done by switching top and bottom flange plates with common dimensions or turning them end for end.

C-5.2.6.6 Welded repairs to Type Y defects are prohibited when the steel to be repaired is 620 MPa or 690 MPa [90 ksi to 100 ksi] quenched and tempered steel. Other steels may be repaired by welding with the approval of the Engineer. Requirements include fairing-in on a 1 on 10 slope, grinding parallel to the base metal surfaces, and avoiding notches normal to the applied stress. If machining or grinding is performed perpendicular to the applied stress, then surface roughness criteria are applied.

C-5.2.6.7 The provisions in this subclause apply specifically to discontinuities longer than 25 mm [1 in] and extend back into the steel more than 25 mm [1 in].

(1) Discontinuities discovered in cut edges, or found as a result of NDT, may have fairly large areas viewed in plan but rarely have much volume because they have negligible thickness. ASTM A435/A435M provides a longitudinal beam UT aimed at finding significant areas of complete loss of back reflection. Complete loss of back reflection may signify separation of the steel in the through-thickness direction. The generous acceptance of large planar discontinuities parallel to the applied stress, as provided by this provision, is based on the knowledge that this form of discontinuity generally does not impair strength or fatigue life. History has not shown these internal discontinuities to be a cause of failure. Occasionally, when laminations form the boundary of a weld joint, gases produced by welding heat may cause voids in

the weld that, because of their size and orientation, may reduce fatigue life. No welding is allowed across edges of laminations or seams normal to applied stress because it concentrates stress and may cause cracking (see C-5.2).

(2) Provided there is no weld discontinuity at the fusion line between the weld and the lamination, Types W and X have little or no effect on performance. Multiple weld passes applied as thin layers not exceeding 3 mm [1/8 in] may be used for sealing off laminations from the primary weld. All filler metals approved for use by this code have sufficient toughness and good compatibility at the weld interface.

(3) If a Type Z discontinuity is surrounded by sound weld or base metal, it is acceptable unless located close to a weld. The high residual stresses created in the vicinity of the weld, the characteristics of the HAZ, and the sharp notch effect of a lamination may cause the lamination to extend into the weld region as a crack. A Type Z lamination does not appear at the groove face for detection prior to welding. However, its presence may be detected when NDT is performed of the completed weld.

If the Type Z discontinuity is within 25 mm [1 in] of the weld groove face, the lamination is investigated. Gouging exposes the lamination, and small weld passes sealing off the lamination from the design weld region may be performed to keep the tip of the remaining lamination at least 25 mm [1 in] away from the design weld. Multiple weld-layers not exceeding 3 mm [1/8 in] are used to seal laminations from the primary weld. At least four layers of SMAW, FCAW-G, or GMAW weld metal are deposited, then SAW (except for active fluxes), SMAW, FCAW-G, or GMAW may be selected to complete the repair. All filler metals approved for use by this code have sufficient toughness and good compatibility at the weld interface.

(4) The area of lamination allowed before replacement or repair is required is described in 5.2.6.7(2). Repairs to areas exceeding these limits may be performed only with the approval of the Engineer.

(5) The maximum length of welded lamination repair is 20% of the length of the base metal edge. This applies to all cut edges and therefore restricts the length of discontinuities in transverse weld groove faces to 20% of the plate width maximum. The Engineer may approve the use or repair of material that exceeds these limits.

If there is sufficient extra length, the defective end of the part may be cut off. If the length is insufficient, the defective end may be removed and a replacement attached by groove welding using a butt joint. Replacement plates and additional CJP groove welds require approval of the Engineer. The minimum flange replacement length should be at least 2.5 times the part width to avoid concentrations of residual stress in the base metal between welds.

(6) All Type W and X discontinuity repairs are made with low-hydrogen electrodes. For Grade HPS 690W [HPS 100W] steel, the maximum electrode diameter is 4.0 mm [5/32 in]. For other grades of steel, the electrode diameter is not limited except by Clause 6. For Grade HPS 690W [HPS 100W] steel, the repair weld quality is inspected no less than 48 hours after completion, and the groove weld is not made until the quality of the repair weld has been accepted by the Engineer. Grade HPS 690W [HPS 100W] steel may experience delayed cracking (see 8.26.1.9).

SMAW repairs made using 3.2 mm [1/8 in] or 4.0 mm [5/32 in] low-hydrogen electrodes produce excellent toughness and are not likely to produce gases from base metal discontinuities. 3.2 mm [1/8 in] electrodes will have lower heat input. The use of higher heat inputs or higher preheat and interpass temperatures should be considered to prevent unacceptable hardening.

(7) Any approved WPS may be used. For Grade HPS 690W [HPS 100W] steel, the maximum electrode diameter is 4.0 mm [5/32 in] on Types W and X discontinuities.

C-5.2.7 When the cut edge of a plate or shape changes direction, the corner of the cut is to have a radius of not less than 25 mm [1 in] between tangents, or 50 mm [2 in] diameter. The rounding of the corner is to reduce stress concentration at the transition of the member, and to facilitate a high quality cut. Reentrant corners made by thermal cutting need to be ground. Drilled holes may also be used to form the radius, then thermal cutting for the straight portions of the cut. Notches in the corner are prohibited, and removed by grinding.

Most reentrant corners are cuts into the section and have an included angle of 90°. Reentrant cuts may be made to allow penetrations by intersecting members or utilities. Intersecting cuts need to be made in a manner that will not create notches that concentrate stress (see Figure C-5.1).

This provision does not address global stress concentrations and fatigue performance at reentrant corners from in-plane or out-of-plane stresses or deformation.

C-5.2.8 Copes are frequently made to floor beam and diaphragm flanges so that members can be connected to the supporting member. Copes allow the elevation of the coped member to come up as high or higher than the supporting member, avoiding interference with the flange of that member. Weld access holes are sometimes needed to provide access at groove welds for welding and inspection. Both copes and access holes form a reentrant corner and the minimum radius requirements of 5.2.7 apply. A smooth transition, with no sharp corners or notches, is required.

The creation of unnecessary stress concentrations should be minimized. Web cuts necessary to form weld access holes should transition gradually and smoothly into the plane of the flange (see Figure C-5.2). The stress concentration is due not only to the change in cross section, but also to the interruption of the residual stress field of the continuous longitudinal web to flange welds.

C-5.2.9 Cutting of base metal may be performed using a variety of processes, including oxygen cutting and plasma arc cutting. However, oxygen cutting and oxygen gouging are not allowed to remove unacceptable weld or base metal, nor are these processes allowed for backgouging. Oxygen deflected by nonferrous or oxidized material in the cutting stream can cause damage to surrounding sound weld and base metal. Air carbon arc and plasma arc gouging are allowed because metal removal is accomplished using compressed air. Compressed air is 80% nitrogen and only removes metal melted by the arc or plasma. Metal removal may be accomplished by any procedure that will not damage the weld and base metal that is to remain.

Air carbon arc gouging should be done using direct current (DC) with the electrode positive, also called reverse polarity. When using electrode positive, the flow of electrons concentrates the heat of the arc in the steel and preserves the rounded shape of the gouging electrode tip. This produces smooth, clean, cuts and gouges when the electrode is manipulated properly. Gouging using AC is also allowed, but the results are less favorable. Gouging using DC with the electrode negative causes the electrode to quickly form a very sharp point. Combined with less effective base metal melting under these conditions, proper gouging is difficult. Copper from the carbon electrode's sheath will also be deposited on the gouged surface.

Failure to direct sufficient air volume and pressure to the electrode tip during gouging, failure to turn on the air before striking the arc, and dipping of the electrode into molten metal that is not removed because of insufficient air pressure at the arc, will contaminate the base metal surface with carbon and may cause excessive hardening and cracking of the weld or HAZ. All thermal cutting and gouging procedures create a HAZ that has increased hardness. The HAZ produced by air carbon arc and plasma arc gouging is normally so shallow that it should be of little or no consequence, particularly on surfaces that will be reheated by subsequent welds. All air carbon arc gouging surfaces should be ground to remove surface irregularities and carbon and copper pick-up from the electrode. When air carbon arc gouging is done properly, little grinding will be necessary to produce a smooth clean surface. Plasma arc gouged surfaces normally do not require grinding, unless unacceptable surface irregularities are present (see NCHRP Report 384 for research concerning plasma arc cutting of bridge steels).

C-5.2.10 Camber in built-up members will normally be provided by cutting the web member to approximate the required finished camber. Weld shrinkage and residual stresses may cause members to change camber during welding. The amount of camber change in bending members will be affected by many things, including whether the tension or compression web-to-flange weld is made first. The greatest amount of camber change often occurs during the cutting of the web plate. Camber changes can occur due to residual stresses induced by mill rolling operations or thermal cutting of nested web plates. Camber change will also depend on how many stiffeners and connection plates are welded to the flanges, the relative mass of the flanges, the nesting of web plates, and other details of welding that shorten areas of flexural members. Extra camber may be cut into the webs of fabricated bending members to compensate for shrinkage losses. At the fabricator's option, members should also have extra length to compensate for axial shrinkage. If the finished piece has excess camber after welding is complete, the member may be accepted without repair, depending on how much excess camber exists. Limited excess camber is accepted by the code (see 5.5.3).

Heating methods may be employed to remove unacceptable excess camber. Corrections to members with less than the specified camber require approval of the Engineer before corrections are made. Those with excess camber may be corrected without prior Engineer's approval. Steels should not be heated above the temperature limits in 5.4.8.2 to avoid the possibility of undesirable transformation products or grain coarsening, or both.

Heat cambering of members may not be permanent. Some camber is generally lost as yield point residual stresses dissipate. When heating is done to decrease camber, and some returns due to relaxation of the residual stress applied by the heating, it generally is of little consequence because of the positive camber tolerance. However, when heat cambering methods are used to correct insufficient camber and the camber achieved is not permanent, the result may be unsatisfactory. All fabricated structural members should be cambered by cutting sufficient design camber, plus shrinkage camber, into the profile of the web(s) before assembly and welding.

C-5.2.11 Quenched and tempered steels may be heat cambered and heat straightened. However, great care is needed when attempting to heat camber or straighten any quenched and tempered steel. The procedure needs to be fully understood and controlled, and requires prior approval of the Engineer. The effective heat cambering temperatures are close to the transformation temperature of the steel, and serious damage can be done to the mechanical properties of the steel, particularly the steel's toughness. Quenched and tempered steels are not to be heated above 600°C [1100°F].

C-5.2.12 Edge Trimming. Edges of material are required to be trimmed, if and as required, to produce a satisfactory welding edge. This subclause specifies that trimming is necessary if the material is welded along its edge, carries a calculated stress, and the thickness of the steel exceeds the specified amount. Rolled edges of shapes and plates are not intended to form the boundaries of groove welds without preparation as they may contain surface discontinuities from the rolling and straightening operations. Any unsoundness such as seams, laps, or laminations in a sheared or rolled edge are to be removed and repaired before welding. Within the limits of groove welded joints, all rolled edges are to be finished by thermal cutting, grinding, or machining, as necessary to produce sound welding surfaces of the dimensions required by the approved details of welded joints. Sheared edges may contain tearing or microcracks from the shearing operation that may lead to weld defects or base metal defects in HAZ areas in thicker materials.

The code addresses sheared edges, rolled toes and edges, and universal mill plate edges. Rolled plate edges do not have any specific contour and are rolled with just a horizontal mill. Universal mill plates have been rolled using both horizontal and vertical mills and subsequently have a more uniform edge. Plate directly from standard horizontal mills may be sheared to the desired width but is more commonly sheared at the fabricating shop. Thicker rolled mill edges may be folded over and encapsulate heavy mill scale within the fold. They are unsuitable for welding until the edges have been trimmed back to solid steel by shearing or thermal cutting, and there is no longer any trace of the original plate edge.

C-5.3 Assembly

The quality of the assembly for welding affects the quality of finished welds and the total cost of welding. Many of the assembly tolerances described in this subclause are based on the difficulty of getting large, heavy, members to fit-up properly. All joints should be assembled for welding using the minimum root opening that is consistent with the access needed to make sound welds. When large root openings are allowed by the code, particularly in the case of fillet welds, it is in recognition that even substantial force cannot push or pull some heavy sections into the desired position. Excess assembly forces may lead to cracking and lamellar tearing because of the high residual stresses created.

C-5.3.1 For fillet welds, intentional separation between parts is typically unnecessary. There is generally adequate separation for shrinkage stresses from the inherent irregularities in edges and surfaces, even when parts appear smooth. The weld metal described by the code is able to sustain residual and applied stresses without cracking, even when the parts joined are in full contact.

When the gap between the connected parts exceeds 2 mm [1/16 in], the corresponding fillet weld leg dimension is increased by the amount of the root opening, regardless of the welding method or process used, in order to achieve the required weld size. No reduction in effective throat is taken when the gap between the parts is 2 mm [1/16 in] or less, and no increase in leg dimension is required. When parts are difficult to bring into contact, sound welds may be made with gaps of up to 5 mm [3/16 in]. The fillet weld produced in that situation may actually become a combination groove-fillet weld because the arc penetrates the root. No design credit is given for penetration at the root, however, regardless of root opening. When heavy sections 75 mm [3 in] or greater in thickness cannot be brought into close proximity, a modified fillet weld may be made with a maximum gap of 8 mm [5/16 in] between the parts by using suitable backing, but only the effective fillet size is considered to carry the load.

The most common use of fillet welds is to join the web to the flange in built-up longitudinal members. Fillet welded joints made with large root openings have an increased risk of weld discontinuities. Good fit-up for welding improves weld quality and significantly reduces the amount of weld metal necessary to make the connection. Less weld metal means smaller residual stress, less distortion, and reduced risk of lamellar tearing and cracks. This assumes that the welds are large enough to carry the stress and result in cooling at acceptable rates.

C-5.3.1.1 Tight fitting backing improves weld quality and the ability to make accurate NDT. Steel backing is to be removed from groove welds in butt joints subject to tension and reversal of stress (see 5.13.3 regarding steel backing).

C-5.3.1.2 Filler plates have a long history of use in bridges constructed with riveted and bolted joints. When filler plates are used to make fillet welded connections in members, as shown in Figures 4.1 and 4.2, and the joint is subject to tension and reversal of stress, the fatigue life of the member may be reduced. A filler plate is part of a welded connection and shown on the design drawings.

C-5.3.2 Parts to be joined by PJP groove welds regardless of the direction of stress should be brought into as close a contact as possible. As root openings increase, the chance that significant weld discontinuities will be formed in the root also increases. In longitudinal welds, porosity and slag in the root may form stress raisers that are normal to the applied stress. Discontinuities, especially with significant dimensions normal to applied stress, may adversely affect fatigue life.

C-5.3.2.1 When parts are difficult to bring into contact, sound welds can be made with gaps of up to 5 mm [3/16 in]. When heavy sections 75 mm [3 in] or greater in thickness cannot be brought into close proximity, suitable backing is needed. The maximum gap using this method is 8 mm [5/16 in].

Large root openings in PJP groove welded joints increase the likelihood of creating weld discontinuities. Good fit-up for welding improves weld quality and significantly reduces the amount of weld metal necessary to make the connection. Less weld metal causes smaller residual stress, less distortion, and reduced risk of cracking. This assumes that the welds are large enough to carry the stress and to produce cooling at acceptable rates.

C-5.3.2.2 The design of bearing joint welds assumes the load to be shared by direct bearing of the steel parts upon each other and by the welds. In such cases, the parts need to be in intimate contact and have no separation between bearing surfaces greater than the amount specified in the contract, generally limited to a maximum of 1 mm to 1.5 mm [0.040 in to 0.060 in]. For bearing stiffeners, see 5.5.9.

C-5.3.4 The table in this subclause describes assembly tolerances similar to those described in Figures 4.4 and 4.5 under the heading "As Fit-Up" for SMAW, FCAW, and GMAW joints. There are minor variations between the tolerances provided in this subclause, as illustrated in Figure 5.2, and the tolerances for the joints in Figures 4.4 and 4.5. For the joints in Figures 4.4 and 4.5, apply the tolerance as provided in the figures for the joints and process as selected.

The tolerances are selected (1) based on good workmanship practices, (2) to ensure, through minimum root openings and groove angles, adequate access to make sound welds, (3) to reduce the risk of single-pass weld root cracks from shrinkage stresses when the root opening is too wide, (4) to discourage the use of excessive weld metal, and resultant shrinkage stresses and distortion because of wider root openings and groove angles, (5) to provide adequate tolerance to the root face dimension so that the root pass does not melt through the material, and (6) to ensure adequate weld size when backgouging is not performed. When joints are to be backgouged, the dimension of the root face is not critical, as long as there is sufficient metal to absorb the welding heat without melting through.

C-5.3.4.1 Because of material and assembly tolerances, groove weld joints may not always fit as desired. When the root opening exceeds that allowed, root opening dimensions may be corrected by adding sound weld metal to produce the intended root opening. Welding across the entire face of the groove may be necessary to maintain the required groove angle. To help control shrinkage stresses that are imposed on the adjacent base metal or structure, corrections are made to the respective groove weld preparation surfaces before the design weld is made. All repair welding is to be done on the free ends of pieces, before joining the pieces together. To control the amount of shrinkage, and distortion, the code limits the correction to twice the thickness of the thinner part, or 20 mm [3/4 in], whichever is less (see 5.2.5.1). More extensive corrections require prior approval of the Engineer.

C-5.3.5 Groove weld preparations produced by air carbon arc gouging are expected to be in substantial conformance with the details for J- or U-groove welds shown in Figures 4.4 and 4.5. This method of joint preparation, compared to machining, is expected to incur more minor deviations, but these are generally not detrimental to weld quality. Exactness of details regarding size and radius are nearly impossible to achieve, therefore reasonable tolerances should be applied. Other groove weld details produced by gouging that are substantially different than those shown in Figures 4.4 and 4.5 are qualified by test and approved by the Engineer prior to use.

C-5.3.6 Proper assembly requires that the parts to be joined be brought into their required position and held until the final welds have sufficient size, and therefore strength, to support all loads on the joint. Parts should not be permanently deformed or damaged in assembling the joint. As pieces increase in size, the strength of the welds or attachment devices holding them may also need to increase. No temporary attachment should be so rigid that parts cannot expand and contract in response to heat from preheating and welding. Tack welding is the most popular method of holding parts to be joined, but tack welds that are not completely remelted by subsequent welds, or welded with an approved WPS with the correct preheat, may cause fatigue cracking problems. Tack welds are not to remain on permanent material outside the finished joint (see C-5.3.7.1). No temporary weld should be made unless shown on the shop drawings or approved by the Engineer (see C-5.3.8).

C-5.3.7 Tack Welds. Clause 3, Terms and Definitions, defines a tack weld as, "A weld made to hold parts of a weldment in proper alignment until the final welds are made." Tack welds are usually small short fillet welds. However, a tack weld may also be a groove weld used to hold parts together prior to final welding.

C-5.3.7.1 This subclause requires that tack welds meet the same requirements as final welds, with a few exceptions as listed in 5.3.7.3. The exceptions deal with tack welds that are remelted. Tack welds that are not consumed in a final weld and are left in the structure require normal quality practices, such as the removal of visible slag or cracks, to ensure that they are sound prior to subsequent weld passes.

C-5.3.7.2 Multipass Tack Welds Cascading the ends of multipass tack welds reduces the potential for incomplete fusion between the final weld and the ends of the tack welds. Incomplete fusion would create stress concentrations at the ends of the tack welds. Cascaded ends of multiple pass tack welds provide a smooth transition for the final welding.

C-5.3.7.3 Remelted Tack Welds Remelted tack welds are exempt from some code requirements because the remelting process eliminates the tack weld. The tack weld metal becomes part of the final weld metal. The code requirement to use Table 6.1 electrodes for tack welding is sufficient to ensure the quality of final welds that incorporate remelted tack welds.

Preheat is not required for remelted tack welds since the remelting process is expected to eliminate any potentially deleterious effects of welding on unpreheated steel, namely potentially hardened HAZs. However, even though preheat is not mandated for such tack welds, the tack welds must be crack-free in accordance with 5.3.7.1.

Given the restraint that tack welds resist, when tack welds do crack, the cracking is typically readily apparent. Visual inspection is generally sufficient assurance that no cracked tack welds are present before final welding. Cracked tack welds should not be confused with broken tack welds (see 5.3.7.5).

High heat input processes such as SAW and ESW typically remelt small, single pass tack welds. Other welding processes and procedures can also remelt small tack welds. However, processes that utilize lower levels of heat input, including some SAW procedures, may not remelt tack welds. The code provides a qualification method to ensure that the final welding process and procedure being used will effectively remelt the tack weld.

C-5.3.7.4 Unincorporated Tack Welds Unincorporated tack welds are usually avoidable, but when they are necessary, they are removed after welding to avoid local stress risers and to reflect sound workmanship. They can simply be ground away.

Depending upon the constraint conditions and size of the components being tacked, it is possible for cracking to occur; when such cracking is observed, the code requires that additional testing be conducted. However, the MT testing and hardness testing prescribed by the code are only required when cracking is observed; these tests are not required for tack weld removal sites that reveal no cracks.

C-5.3.7.5 Broken Tack Welds The code makes a distinction between "cracked tack welds" and "broken tack welds." Tack welds that fracture because of self-restraint and residual stresses are said to be "cracked." Tack welds that sever because of handling loads or thermal expansion that occurs during subsequent welding are said to have "broken."

Tack welds are usually small and may break during fabrication due to overstress from local restraint conditions. Broken tack welds can be repaired or removed if they break prior to final welding operations. However, tack welds may break ahead of an advancing welding arc due to thermal expansion from welding and preheating. If final welding of a specific joint is already underway, it is more deleterious to stop final welding and repair the tack weld than to simply weld over it, so this practice is allowed.

Conversely, cracked tack welds should not simply be welded over. Broken tack welds that break during welding have cracks that are typically normal to the direction of applied load/restraint, and are easily distinguished from cracked tack welds that occur before final welding and have fractures with more unpredictable orientation.

C-5.3.7.6(2) Tack Welding Outside of the Joint. Intermittent welds that attach longitudinal backing to the steel, made outside the joint, can be problematic under fatigue loading. Hence, the code provides two options for attaching backing: it may be with tack welds made in the joint (where they will be incorporated into the final weld), or it may be attached by fillet welds outside the joint, but such welds are required by the code to be continuous. The preheat, qualification, and quality exemptions of 5.3.7.3 do not apply to these external tack welds.

C-5.3.8 Temporary Welds. Temporary welds should be made and removed with great care because they are often smaller than permanent or final welds in size and length. When the stress range and numbers of cycles of stress were sufficient in fatigue testing, cracks have initiated from sites where temporary welds have been removed. The smaller temporary welds provide limited welding heat input, causing hardening of the base metal to a limited depth, even though the welds appear to have been removed. Even though an approved WPS is required, small and even medium size temporary welds are generally subjected to higher transformation cooling rates, increasing the risk of hydrogen-assisted cracking in the weld or base metal. Because of the lower welding heat inputs that are common in temporary welds, as compared to other welds, higher preheat and interpass temperatures should be considered. The hard portion of the HAZ, if any, under a temporary weld is generally shallow. If removal is carried to 3 mm [1/8 in] below the original surface and is carefully faired-in on a 1:10 slope, there is little chance that the site will initiate fatigue cracking under any loading condition. All weld removal sites should be carefully visually inspected for the remains of fusion defects, notches, and cracks. MT or PT may be used to supplement visual inspection (see 5.3.7.4).

Because of the risk of HAZ cracking and crack propagation in quenched and tempered steels, including Grades HPS 485W [HPS 70W] and HPS 690W [HPS 100W], the use of temporary welds in tension areas is prohibited.

Temporary welds on exposed weathering steel should be made using weathering steel electrodes. The area of nonweathering steel electrode may corrode and cause staining.

All temporary welds need to be shown on the shop drawings. This enables the planning and inspection required for the use of and removal of temporary welds.

Temporary welds are similar in properties to tack welds not incorporated into final welds, covered under 5.3.7.4. Incorporated tack welds and their HAZs usually benefit from the heat input of subsequent weld passes, but temporary welds do not receive this additional heat input.

C-5.3.9 Joint Root Openings. The root opening dimension controls access for welding in all groove welds with an included angle of 60° or less. When there is less than adequate root opening, the number and size of fusion discontinuities can be expected to increase. When there is too much root opening, in joints that are not made against steel backing, it is difficult or impossible to bridge the root opening with sound weld metal. Excess root opening causes weld discontinuities and allows the degradation of molten weld metal in the root because there is insufficient shielding on the far side of the joint. These defects, fortunately, are removed by backgouging and do not become part of the permanent weld. In joints made using steel backing that have excessive root opening, a single-pass weld at the root may be too wide and thin to sustain transverse shrinkage stresses, and therefore crack.

Manually controlled open arc WPSs have a greater ability to successfully bridge root openings than fully automatic machine-controlled WPSs that weld in a straight line without being programmed to weave. Machine controlled WPSs produce stringer beads under the provisions of this code, and unless otherwise approved by the Engineer, root openings are limited to a maximum variation of 3 mm [1/8 in] from minimum to maximum, when measured along the joint as assembled for welding. This provision for mechanized welding applies to both open root weld joints and joints made against steel backing. It assumes that machine guidance control is inferior to manual guidance of the arc. Unacceptable deviations in root openings are allowed to be repaired by welding, machining, or grinding prior to assembly (see 5.3.4).

C-5.3.10 Assembly Sequence. Groove weld preparations produced by air carbon arc gouging are expected to be in substantial conformance with the details for J- or U-groove welds shown in Figures 4.4 and 4.5. This method of joint preparation, compared to machining, is expected to incur minor deviations that are not detrimental to weld quality. Exactness of details regarding size and radius are nearly impossible to achieve, therefore reasonable tolerances should be applied. Other groove weld details produced by gouging that are substantially different than those shown in Figures 4.4 and 4.5 are qualified by test and approved by the Engineer prior to use.

C-5.4 Control of Distortion and Shrinkage

C-5.4.1 Weld shrinkage stresses are unavoidable, but the magnitude of residual stresses and resulting distortion can be reduced by careful planning, reducing weld sizes, reducing the yield strength of the filler metal, and reducing the number of weld passes required to produce a given volume of weld metal. To minimize weld shrinkage stresses, welds should be no larger than necessary. Filler metal yield strength should not significantly "overmatch" the base metal, allowing the weld metal to yield under residual stress rather than deliver higher shrinkage stresses into the member. High weld metal strengths cause high residual stresses in the weld and adjacent base metal, and also exhibit lower ductility. Multipass welds should be made with no more stringer beads than are necessary to produce good mechanical properties in the weld metal. Multipass welds are desirable because they have improved mechanical properties, but an excess of small weld passes creates additional residual stress. Each pass requires sufficient heat input to fuse to the adjacent weld and provide a slow enough cooling rate to avoid problems.

Preheating can help reduce residual stress. The parts expand from heating before welding and cool more slowly, resulting in a weld area with lower residual tensile shrinkage stresses after the weld cools to ambient temperature. Sequence of welding generally has more effect on angular distortion than on total residual stress.

Following solidification, welds and base metal contract as temperatures decrease. Unrestrained, steel contracts about 2 mm per 100 mm [1/16 in per 4 in] as it cools from liquid form to a room temperature solid. Steel in the form of austenite, above the transformation temperature, contracts at a faster rate than it does after transformation to ferrite, pearlite, bainite, or martensite. At transformation, there is an expansion that actually reduces the residual stress, but contraction continues as temperatures decrease. The effect of all cooling after solidification in welding is to create net residual tensile stress in the weld, and compressive stress in the steel, whenever restraint is present. The higher the yield strength of the steel transformation product, the higher the residual stress. Each weld pass causes shrinkage and resulting residual stress.

All welds, regardless of size, produce longitudinal residual stresses equal to the yield strength of the weld. In general, by the time a weld is 200 mm [8 in] long, it has developed yield strength residual stresses. These stresses act on the full length of weld. Stress is concentrated at the ends of welds and where there is a discontinuity or geometric change in section. When hydrogen-induced cracking has occurred, weld removal may reveal a pattern of underbead cracking at regular intervals along the full length of the weld. In addition, hydrogen-induced cracks frequently outline ends of welds where stress is concentrated.

In addition to longitudinal residual stress, which should always be considered to be at yield strength, there are also significant transverse residual stresses. Transverse residual stresses vary depending on weld size and location in the weld. A double V-groove weld, BU-3, may have a transverse tensile stress at the surface of one-third to one-half the yield strength when the weld size is 50 mm [2 in] or greater. The larger the weld nugget, the higher the transverse residual stress. The transverse residual stress at the center, or root, of a two-sided groove weld is a compressive stress. Since weld passes are completed in the root first and all subsequent weld passes shrink against the resistance of the original weld passes, welds made by traditional arc WPSs have transverse tensile stresses at the surface, welded last, and compressive stresses at the root. The root of the weld can be at the center of the weld cross section or at a surface, depending on the joint detail used. ESW and EGW welds have the opposite residual stress pattern, because they solidify from the edges of the weld pool towards the center. This places the center of the weld in tension and the surfaces in compression.

Attempts to control shrinkage and distortion should be based on the effects of residual stress from weld solidification, transformation, and cooling, and also the stresses and dimensional changes produced by the process of heat shrinking, or upset shortening. Upset shortening, thickening and shortening of the material, occurs in all weld metal and HAZs that do not remelt under the heat of subsequent passes of weld. The weld and base metal is heated or reheated by each pass of the welding arc. Upset shortening is caused by the rapid expansion of the steel and existing weld at high temperature, followed by contraction during cooling, with rapidly increasing restraint, causing localized yielding and thickening of the material. It is similar to the phenomena used to camber, curve, or straighten steel bridge members using heat. In welding, temperatures are high and the restraint of the surrounding steel is more than sufficient to produce upset shortening without any need for preloads.

C-5.4.2 Welds are to be made so that shrinkage does not produce unacceptable angular distortion in weld joints, or permanent sweep or camber in the member. If equal amounts of weld metal are placed sequentially on each side of an initially unrestrained, two-sided weld, the first side weld will cause more angular distortion than the second side weld, which is then restrained by the first. The result of welding with equal weld volumes on each side of a two-sided butt joint groove weld, for example, is noticeable and perhaps unacceptable angular change, unless the parts were either angled slightly before welding in anticipation of this condition, or restrained against rotation (see C-4.1.2). If butt joint groove welds made without restraint or initial compensating misalignment are to be straight after welding, either the second side weld volume needs to be considerably larger than the first side weld or weld passes need to alternate sides. Typical estimates for differential weld volumes to produce straight butt joints indicate that a second side volume between 50% and 100% larger than the first, or between a 60–40 and a 67–33 split, depending on joint design and restraint, is needed. If the first side weld causes serious angular distortion, unbalanced welding on the second side may not be able to bring it straight, and may result in extremely high residual stresses, base metal deformation, or even hot "restraint" cracking.

For small assemblies, alternating weld passes between opposite sides may reduce deformation and residual stresses, but this is not practical for flanges or other large weldments.

Longitudinal welds not located about the center of gravity of the cross section induce sweep or camber, or both, in the member. Longitudinal shrinkage and distortion are more difficult to estimate because weld size, member stiffness, distance from welds to the member's center of gravity, and sequence of welding have an effect. Good weld design and sequencing considers balancing welds about the center of gravity of the cross section, and placing the welds in a pattern that will minimize curving and twist of the member.

C-5.4.3 Distortion control and avoidance of shrinkage stresses that can lead to cracking or lamellar tearing require planning, including the selection of the weld process, filler metal, and joint details to be used. These items should be indicated on the shop drawings and in the WPS. Where shrinkage and distortion are likely to be a problem, a special weld sequence drawing should be prepared listing all steps necessary to control joint or member distortion. The Engineer should be provided with this information, but approval is not required.

C-5.4.4 When welding is done from points that are relatively fixed toward points that are unrestrained, transverse weld shrinkage stresses may be used to bring large parts into alignment. Welding from the fixed portion toward the free end in built-up members, typically from the center outward, reduces the risk of buckling and the separation of parts from member distortion caused by weld shrinkage stresses. Made in this manner, the cooling of the welds at the ends causes a longitudinal compressive effect near the center of the member, helping offset the accumulation of tensile shrinkage stresses near the center. If the ends of a part are joined first, the weld near the center is more restrained, increasing the risk of transverse shrinkage cracking.

C-5.4.5 Shrinkage from one weld may have a major effect on other welds or member components. Welds should always be made with the minimum reasonable restraint that is consistent with production and dimensional requirements. The weld metal is designed to sustain yield strength residual stresses without cracking. The base metal is often first to fail in situations of high restraint and high residual stress. When stresses are in the through-thickness, or "Z" direction, lamellar tearing can be a serious problem.

The sequence of welding joints should be considered. Generally, joints with high restraint or high shrinkage should be welded first, followed by joints with less restraint and shrinkage. Should the joints with lesser restraint be welded first, the more difficult joints may have even more restraint than if welded first. Spacing materials in the joint, particularly at the root, have been used successfully in some cases to provide allowance for weld shrinkage.

C-5.4.6 When cover plates, flanges, and longitudinal stiffeners are completely joined full length before being welded to their respective beams or webs, residual stresses are kept to a minimum. The butt joints are welded without longitudinal restraint, so the residual stress from the subsequent longitudinal welds is not added to the transverse residual stresses created by the welds used to join the member components. When all longitudinal components are joined before being welded into their final cross section, there is better access for welding and weld quality is often improved.

Long members may be spliced by welding in the shop or field. Splicing of finished full section members will generally be done by welding in a single transverse plane as described in 4.17.6.2. Welding in this manner requires special care because of the large sections, high restraint, and triaxial stresses present. Special care is needed to avoid cracking near weld access holes because of residual and applied stresses that may be concentrated by the change in section. If the access hole is finished to remove all notches that concentrate stress, and if all untempered martensite produced by thermal cutting is removed from the surface of the access hole by grinding, unfilled access holes may provide satisfactory fatigue performance.

C-5.4.7 Partially completed welds may crack if allowed to cool down before the weld is complete. This is particularly true for small initial root passes when the parts being joined are both large and highly restrained. The cracks that occur may be hydrogen-induced, but are more likely to be shrinkage cracks from thermal changes or increased restraint. Shrinkage cracks may form because the weld is under severe stress, but the elevated temperature of the weld or HAZ has reduced the strength of the material below what is required to resist cracking, although hot weld material is generally quite ductile. With hydrogen-induced cracking, the weld region has not been allowed to remain at elevated temperature long enough to diffuse sufficient hydrogen from the weld and HAZ. When welds are completed before cooling is allowed, there is more weld metal to share the stress and the weld and HAZ is hot for a much longer period. In addition to the benefits of more time at temperatures that facilitate diffusion of hydrogen, steel temperatures above 200°C [350°F] make hydrogen-induced cracking almost impossible. Completed multipass welds have more weld passes that have contributed to the improvement by heat treatment of formerly deposited passes.

C-5.4.8 All bending and straightening methods affect weld and base metal properties to some degree. Research on bridge repair indicates that the upset shortening method utilizing passive restraint has less effect on final steel properties than mechanical methods with or without the application of heat, but displacement produced by heat-assisted mechanical methods is more predictable and efficient.

Editions of the code prior to 2020 only permitted heat straightening of fracture critical members by the upset shortening method. However, research focusing on the influence of heat and strain on the toughness and ductility of steel has determined that realigning the material at room temperature by imposing relatively small strains does not significantly degrade the mechanical properties of the material.[1]

(1) Mechanical methods without heat (“cold bending”), such as press-break bending, opposed roller bending, or “gagging” (three-point loading without impact), may be used if force is sufficiently distributed to avoid causing gouges or abrupt kinks. The practicality of using mechanical force alone without heating may be limited based on material thickness and the proximity of other elements. For elements close to welds, tensile stress induced at the weld toe are significant, so careful inspection of that area is necessary following the procedure. Keeping mechanical pressure on elements to maintain the corrected orientation while members are welded may result in increased residual stresses.

(2) Applying mechanical forces prior to a set of heating patterns for upset shortening may increase the angular change achieved by a factor as high as four as the restraint creates greater upset shortening. Heat straightening by upset shortening with mechanical preload is not “hot bending” or heat-assisted mechanical bending, which applies force at elevated temperatures below the transformation temperature, using the reduced strength and increased ductility to adjust streel with less force. “Hot bending” was traditionally used in cases when “cold bending” (mechanical bending without heat) was prohibited in versions of this Code prior to 2020 and of the AASHTO specifications prior to 2012. In those earlier versions of the Code and the AASHTO specifications, no lower limits were placed on the application of heat, but bending material while it is in the “blue brittle” range carries an increased risk of fracture. Heat assistance for mechanical bending now requires approval and must remain within the temperature limits of 5.4.8.

C-5.4.8.2 During heat straightening, careful attention is needed to avoid overheating the steel. The limits provide a margin of safety to avoid reaching the transformation temperature which could degrade the mechanical properties of the steel. Techniques for monitoring the steel temperature vary. For example, with oxy-fuel heating, the temperature is typically taken 5 to 10 seconds after the flame leaves the area for a more accurate reading. Heating quenched and tempered steels beyond their tempering temperature can cause loss of strength.

Hot working, which employs high strains above the transformation temperature, is prohibited by way of the upper limits on heating temperature. It results in diminished mechanical properties (ductility, strength, toughness), and may initiate cracks that can propagate in service.

1. Keating, Peter B. and Christian, Lee C. 2012. “Effects of Bending and Heat on the Ductility and Fracture Toughness of Flange Plate”, Texas Transportation Institute, Report No. FHWA/TX-10/0-4624-2.

C-5.4.8.4 The temperatures between 150°C [300°F] and 370°C [700°F] represent the "blue brittle" range where steel ductility is low and the application of external force is more likely to lead to fracture. The minimum of 5°C [40°F] is to avoid brittle behavior at low temperatures and preclude ice which could impede temperature measurements or conceal defects.

C-5.5 Dimensional Tolerances

C-5.5.1 The equations listed give the maximum offset from a straight line that would represent a perfectly straight member. Straightness should be measured about both the strong and weak axes of the member. These provisions are to provide safety against buckling of compression members. No provision is made for local deviations. Deviations from a straight line should be gradual and the maximum deviation should be near the middle of the member.

The tolerances for rolled sections are governed by ASTM A6/A6M (AASHTO M160M/M160). The requirements for built-up columns in this subclause are identical to the ASTM A6 requirements for "certain [W and HP] sections with a flange width approximately equal to depth."

C-5.5.2 This equation provides tolerances for the maximum deviation from a straight line that would represent a beam or girder, regardless of cross section, that had no specified camber or sweep. For beams and girders with a specified camber, see C-5.5.3. Camber deviations are vertical displacements from the specified no-load condition. Sweep deviations are horizontal displacements from a perfectly straight alignment. There are no provisions for localized abrupt changes in alignment. Deviations from a perfectly straight vertical and horizontal alignment are expected to be gradual.

The tolerances for rolled sections are governed by ASTM A6/A6M (AASHTO M160M/M160). The requirement of this subclause is identical to the ASTM A6/A6M (AASHTO M160M/M160) requirements for camber and sweep in rolled W and HP shapes not used as columns.

C-5.5.3 The tolerances for beams and girders that have specified camber are divided into two categories. The second set of tolerances is applicable when the top flange is embedded in concrete and a designed concrete haunch is not used. A "design concrete haunch" may be defined as the use of additional concrete above the top of the beam or girder flange to adjust for elevation, with a given concrete depth between steel flange and the underside of the concrete deck. The first set of tolerances apply for those cases where the top flange is not embedded in concrete, and those that employ a designed concrete haunch. The tolerances of the second set are established as a plus or minus from specified camber. In the first set of tolerances, there is no provision for negative or inadequate camber. Instead, the tolerance is applied as a plus only tolerance. The physical sum of the tolerances is the same for both sets, 40 mm [1-1/2 in] for longer spans, and 20 mm [3/4 in] for shorter spans, as defined. Tolerances are applied to the span length (bearing to bearing) of the girder line, not individual girders in the line.

The tolerances were first developed for bridges constructed with a minimum bridge deck design haunch of 50 mm [2 in]. When bridge deck slabs are designed in that manner, excess, positive, upward camber up to 50 mm [2 in] can be accommodated during construction. Excess camber in amounts less than the haunch height would cause no difficulties with the bridge slab or other components, provided adjacent members had similar camber profiles. The camber tolerance is +40 mm [1-1/2 in], with the remaining 10 mm [3/8 in] provided as a contingency for other field deviations (see Figure C-5.6).

The tolerances are applied at the lay-down stage when members are pre-assembled for drilling holes for field splices or preparing joints for field welded splices. The tolerances are measured as the offset between the arc of the specified camber and the location of the steel. The arc is based upon an assumed typical uniformly distributed loading case that causes a parabolic deflected shape.

Not all camber is permanent. As residual stresses are dissipated, in time, due to applied handling and live loads, the profile of the steel changes. Camber produced by web cutting is most permanent and is the primary method of cambering bridge members provided in the code (see 5.2.10). Camber induced by heating is subject to camber loss, especially prior to deck placement, with the amount of loss dependent on the maximum ordinate and the heating method used, and is allowed only for the correction of camber. Members that are heat curved may change camber as a result of heat curving. Extra camber should be cut into the webs of members to compensate for losses from residual stress dissipation and weld shrinkage effects. The greatest change in camber often occurs when cutting the web plate to size. Stress from mill rolling may be released at that time and substantial camber change, both plus and minus, can occur. This can be minimized by precutting the plate before cutting to final size. This camber change is most significant when cutting two pieces from a larger plate.

Other camber loss can, in most cases, be controlled by the moderate addition of camber in the cutting pattern. This extra camber is usually determined by the "intuitive" judgment of shop personnel.

The camber specified should allow ease of construction and not negatively impact function or aesthetics. Excess, positive, upward camber rarely causes any problem in construction, provided the deviations from specified lines are gradual and the maximum deviation is not so large that the steel intrudes into the design slab or is misaligned with connections to adjacent members.

C-5.5.4 This subclause provides a method of calculating the maximum horizontal deviation from a specified sweep. The maximum deviation is expected to be near the center of the piece or assembly, unless otherwise specified on the design drawings, and deviations are expected to be gradual rather than abrupt. Deviation from specified sweep in horizontally curved bridge members is measured as the deviation from the specified horizontal curve shown on the approved drawings. This does not require uniform curvature or preclude "chording" due to heat cambering at intermediate points, provided the member stays within the tolerance limits. Most bridge members are flexible and allow some lateral adjustment during erection without damage. Box members are much stiffer than I-shaped members. Deviation from specified sweep should not be so large that it is difficult to align connecting members and cause damage to the steel during erection.

Flange plates are often thermally cut from wider plates. It is recommended that both edges of plates are cut simultaneously to maintain balanced heat. Failure to do so may result in undesirable sweep or twist in the flange plates.

The tolerances expressed in this subclause are identical to the mill tolerances from straightness given in ASTM A6/A6M (AASHTO M160M/M160) for W and HP sections.

C-5.5.5 This is a historic workmanship standard that also represents good design. The web location may deviate 6 mm [1/4 in] to either side from the center or other specified location at the flange.

C-5.5.6 The provisions for web flatness are based upon aesthetics and relative freedom from web buckling and are contained in 5.5.6 (1) – (4). These provisions do not apply to rolled sections, which do not have the same issues of workmanship and potential buckling. Lack of web flatness is most pronounced on facia girders that are painted with glossy-type paints and is sometimes referenced as reflective distortion or oil canning.

C-5.5.6(1) Measurement of Web Flatness. The web's variation from flatness is the distance from the actual web surface to its theoretical location, measured normal to the plane of the theoretical web. The web face is presumed to be in its theoretical location at panel boundaries. Measurement of web distortion considers the curvature of the member and deducts the curvature arc from the actual distortion dimension. See Figure C-5.4.

C-5.5.6(2) Flatness of Girder Webs. Web distortion is exacerbated by using thin web plates, using fillet welds that are larger than necessary to attach any intermediate stiffeners and connection plates, and by heat curving of girders to short radii after the completion of welding. Some designers consider 10 mm or 12 mm [3/8 in or 1/2 in] to be the minimum plate girder web thickness to avoid significant distortion and avoid the need for large numbers of transverse intermediate and longitudinal web stiffeners.

Most bridge girders have a web depth of 1200 mm [48 in] or more. While 8 mm [5/16 in] fillet welds are commonly used to attach intermediate stiffeners and connection plates, 6 mm [1/4 in] fillet welds are typically better for the connection of one-sided intermediate stiffeners to the webs of fascia girders. Welds of this size reduce the amount of stiffener "reflection" distortion that occurs in the unstiffened side of fascia girders.

The material savings gained by using thinner webs are often more than offset by the increased labor costs necessary to install the stiffeners, and to correct the web distortion that may result.

Heat curving members with heavy, wide flanges and radii under 300 m [1000 ft] can create severe web distortions ("oil can" effects). Precutting or precurving the flanges before attachment to the web will reduce these effects. Improper use of heating torches when preheating for welding can cause serious distortions as well. Unstiffened areas of girder webs should be protected from concentrated, high intensity heat.

To reduce lateral distortion when correcting distortion by heat-shrink methods, heating should be done near intermediate stiffeners or connection plates whenever possible. If care is not taken, the heating patterns may cause distortions that will remain visible throughout the life of the structure.

C-5.5.6(3) End Panels. Provisions for out-of-flatness of girder webs in end panels with bolted splices are described in 5.5.6(3). End panels with bolted splices are permitted twice the maximum out-of-flatness allowed elsewhere in the girder. This is because there is no lateral support along one edge for the relatively thin web while the other three sides of the panel are being welded. Lateral displacements of 100 mm [4 in] or more are possible in deep girders. Temporary distortions of this type should not be cause for repair. The installation of high strength bolts in the web connection tends to straighten the web without the use of excessive force, and without damaging the member or its connections.

Although the web-ends may have the distortion allowed by this subclause when each girder segment is in the web-vertical position, adjacent webs and their splice places are brought into common alignment prior to shop drilling splices. Drilling holes with the webs fully displaced to the allowable tolerances would lock those displacements into the completed structure. For large segment displacements, special field bolting and pinning may be needed to bring webs and splice plates together before routine bolt tightening is performed.

C-5.5.7 This is a historic workmanship provision that has produced good results for I- or H-beams and girders. For a completed web flange-to flange intersection to be square, components must be properly oriented before welding. Fixturing the flanges against rotation during welding and sequencing the welding to avoid rotation are also helpful in providing a square joint. Multipass welds should be deposited in a manner that will balance shrinkage stresses on each side of the web-to flange weld.

Generous tilt tolerances are provided for locations between bearing points. Parts to be joined by welding or bolting need to align in assembly. The flanges need to be approximately square with the web, or at least have the same tilt as the adjacent pieces, where splices are to be made.

Similar to I and H shapes, tilt and warpage (flatness) tolerances apply to the flanges of box or tub girders regardless of the orientation of the web(s).

At bearing points, the flanges should be normal and square with the vertical centerline of the member (see 5.5.9). Bearing stiffeners facilitate achieving flat bearing surfaces, particularly when combined with a finish-to-bear and fillet welded bearing stiffener-to-flange joint.

C-5.5.8 These dimensional tolerances have produced good results and are considered reasonable workmanship tolerances. The strength variation caused by such tolerances is nominal.

Bridge seats are provided an elevation tolerance, bearing heights have a tolerance, and fabricated steel members have both camber and depth tolerances. The result, after erection, is that the top of steel may not always be exactly at the elevation shown on the plans. However, this seldom causes difficulty in construction or use. Where the maximum of these combined tolerances is not acceptable, tighter limits should be noted on the plans. The use of shims may also alleviate problems with member elevation.

Web depth tolerances at welded member splices may require tighter tolerances than that provided in this subclause. The adjustment for depth variation through the alignment of parts is limited as described in 5.3.3.

Depth of rolled sections is governed by ASTM A6/A6M (AASHTO M160M/M160).

C-5.5.9 Bearing loads are expected to be carried by steel parts that bear upon each other. Bearing does not necessarily mean full contact, but as close as specified. It is not essential that the parts bear completely before all loads are applied. The applied loads can close very small gaps and the elastic or plastic strains on adjacent welds are of no consequence, provided the steel components fit as specified. Stiffeners should bear after the dead load has been applied. (see Figure C-5.8).

When bearing stiffeners are used, at least 75% of the bearing stiffener area at the bearing end of the stiffener is required to bear against the flange. Typically this will be the bottom of the bearing stiffener bearing against the top of the bottom flange.

Rationale: In the case of a steel pier or bent supporting other members, the relevant flange under the supported members will be the top flange.

For girders using bearing stiffeners, at least 75% of the bearing area directly below the web and stiffeners is required to be within 1 mm [1/32 in] of the supporting seat or base. The flange not directly below the web and stiffeners need not be within this tolerance.

Rationale: This is not about expectations, this is about describing what the code actually does require.

For girders without bearing stiffeners, only the area beneath the web is required to be within 1 mm [1/32 in] of the seat or base. In addition, the flange should not be curved or bent such that the bearing contact area is at the edges of the flanges rather than beneath the web.

C-5.5.10 Intermediate stiffeners are intended to prevent web buckling. They may also brace the flanges during handling and transportation and help avoid web cracking caused by flange rotations about the web due to those operations. It is not essential that intermediate stiffeners have a finish-to-bear fit upon adjacent flanges. A small gap of up to 2 mm [1/16 in] is allowed. When tight fit to both flanges is required, typically the intermediate stiffeners are cut to a length slightly less than the exact distance between flanges, then placed tight against the tension flange and welded to the compression flange. Stiffeners are usually welded to webs before they are welded to flanges, and the shrinkage from the web weld may cause the stiffener to pull slightly away from the flange. The flange may also rotate away from a stiffener that was originally in contact. A slight separation is not structurally detrimental, but may be a corrosion problem if not properly protected. A tight fit of stiffeners may be beneficial in maintaining squareness of flanges (see 5.5.7).

C-5.5.11 This is a reasonable workmanship standard. Removal of a bowed or out-of-alignment stiffener that may exceed this limit should be weighed against added web distortion and other fabrication problems incurred during the repair (see 5.7.5).

C-5.5.12 Bearing stiffeners act like columns, fixed on one side and unsupported on the other. Bearing loads are transferred from the girder web to the flange through the stiffener. Eccentricity, caused by lack of straightness, is undesirable. Bearing stiffeners may be perpendicular to flanges or truly vertical, subject to contract requirements and alignment considerations, especially on skewed structures. Because bearing stiffeners concentrate bearing forces at designated locations on the seat or base below, the location of the bearing stiffeners is critical.

C-5.5.13 When special dimensional tolerances are required, they should be described in the contract documents. Tolerances may be established for structural, workmanship and aesthetic reasons. Some tolerances have a major effect on whether or not pieces will fit together properly during erection, others affect how the structure will function and others affect appearance. All special requirements for dimensional tolerances should be based on the needs of the individual structure.

Because it is difficult to specify properly, and because the effect of twist varies greatly depending on the type of member and its application, a tolerance on twist is not provided in this subclause. Twist of box members, sometimes 1000 times more torsionally stiff than I-shape members, may seriously affect ease of erection and secondary stresses. Most twist problems are a result of poor assembly. The best way to avoid problems in the construction of box members is to fit the box properly and hold it in position firmly while making the corner welds in a sequence that will balance shrinkage stresses. For box girders, elements are expected to be straight or have matching curvature or camber prior to assembly. That is, the top and bottom flanges should match and the webs should match each other. Internal diaphragms also help to keep box members free of twist and aid in their assembly.

It is extremely difficult to straighten unacceptable twist in box members. Often the only solution is to remove the corner welds, reposition components, and replace the welds. If there are problems with dimensional tolerances of finished members, the Contractor should propose solutions for approval by the Engineer.

C-5.5.14 Faying (contact) surfaces of adjacent members to be connected by high strength bolted splices should be nearly co-planar to avoid requiring splice plates to be excessively distorted in their weak, through-thickness direction. Fills of 2 mm [1/16 in] or less are difficult to blast, prime, and assemble without damage or distortion. The clamping force of the bolts is able to correct slight angular misalignment, but cannot significantly distort splice plates without straining the splice beyond yield. When the splice material is too thick to bend into contact, a poor connection may be produced. When excessive bending of splice material occurs, the splice may be damaged. Filler plates are allowed to compensate for differences in thickness at bolted connections, unless otherwise provided in the contract documents.

C-5.5.15 For secondary members, additional bending of splice material is allowed because the potential for future fatigue damage is less and failure would not jeopardize the overall structure.

C-5.5.16 The assembly and fit-up tolerances of 5.3 apply. Conformance to these requirements is facilitated by shop assembly or by preparing the joint to a template.

C-5.6 Weld Profiles

Rules for acceptable weld profiles have been established to ensure good workmanship and to avoid unnecessary stress concentrations.

C-5.6.1 Fillet welds' shape should not create excessive stress concentrations. Excess convexity can concentrate stress at the weld toes. Excess concavity creates surface shrinkage stresses at the center of the weld face that may contribute to throat cracking. Ideally, fillet welds should appear as shown in Figure 5.4(A). Welds conforming to the requirements of Figure 5.4(B) are acceptable provided the convexity limits have not been exceeded. Welds shown in Figure 5.4(C) are not acceptable if they exceed the limits of convexity, undercut, overlap, and size. The maximum convexity of a fillet weld and of individual fillet weld passes is a workmanship standard.

At the very end of fillet welds, because of surface tension and the inherent nature of starting and stopping the weld, it is extremely difficult to produce completely acceptable weld profiles. Where an intermittent fillet weld is used, the weld profile may deviate from the specified profile for a short distance at the beginning and end of the weld, provided the deviation is located outside the required length of weld. Undercut in excess of code requirements and significant weld discontinuities are still not allowed, even if outside the effective length of the required weld.

C-5.6.2 Groove welds in T-joints and the inside face of corner joints are reinforced with fillet welds (see 4.11.3). Excessive reinforcement may be an indication of improper weld procedure or technique that should be corrected. The weld metal should transition smoothly into the base metal, and there should be no surface notches to concentrate stress or hinder effective visual inspection. Figure 5.4 shows acceptable and unacceptable groove weld profiles.

C-5.6.2.1 When a groove weld is required to be finished flush, the code has limits on reduction of both thickness and overall cross section to ensure that the finishing operation does not overly reduce the cross section of the weld. This provides for some localized grinding below flush or undercut removal but restricts excessive removal over a large length of the joint.

C-5.6.2.2 When the surface is required by the Engineer to be finished, surface measurements limitations are applicable. Surfaces finished to between 3 µm and 6 µm [125 µin and 250 µin] have the finishing lines parallel to applied stress. This requirement is applied to all welds but has little effect on the performance of welds carrying only compression. Welds finished to equal to or less than 3 µm [125 µin] may be finished in any direction. For welds in butt joints carrying applied tensile stress, the maximum surface roughness is 3 µm [125 µin].

C-5.6.3 Overlap creates a stress concentration at the toe of the weld. It may have a significant effect on fatigue life when normal to the applied stress, such as reinforcing fillets on CJP groove welds in corner and T-joints in tension. Overlap also makes it more difficult to measure weld size, verify fusion, and perform visual inspection.

C-5.7 Repairs

C-5.7.1 Weld metal and portions of the base metal may be removed by any process that will not permanently damage the steel and weld which is to remain. Sound weld and base metal should not be removed unnecessarily (see C-5.2.9 for restrictions on the use of thermal cutting and air carbon arc gouging). Cut surfaces are thoroughly cleaned before initiating, or continuing, a repair. Repair welding is done using an approved WPS.

Because repair welds are often made under conditions of severe restraint, techniques important to make a good weld in the original construction should be followed with even greater care during repair welding. When the weld repair WPSs has a lower heat input than the WPS used to make the original weld, or when the repair weld is a relatively small localized weld, preheat and interpass temperatures higher than those used in production welding should be considered to prevent excessive hardening of the weld or HAZ.

C-5.7.2 When unacceptable weld discontinuities are found, the Contractor has the option of either repairing the weld or weldment, or providing a complete replacement. Without the approval of the Engineer, the Contractor does not have the authority to remove or repair unacceptable welds or base metal with certain types of cracks, weld discontinuities, or base metal discontinuities as described in 5.7.4. The repaired weld should conform to the requirements of the original contract documents, and is subject to the same inspection and acceptance criteria as the original weld. All routine repairs by welding are expected to conform to the requirements of 5.7.2.1 through 5.7.2.4.

C-5.7.2.1 Overlap or Excessive Convexity. Removal of excess weld metal may be done by air carbon arc gouging, machining, chipping and grinding, or grinding. Gouged or cut surfaces should be cleaned and finished by grinding (see 5.2.9).

C-5.7.2.2 Excessive Concavity of Weld or Crater, Undersize Welds, Undercutting. Prior to welding, the surfaces are expected to be cleaned in conformance with 5.11.1. Additional welding, following an approved WPS, is then performed to provide the proper weld size and profile.

C-5.7.2.3 Excessive Weld Porosity, Excessive Slag Inclusions, Incomplete Fusion. It is important to remove these weld discontinuities. However, to reduce the number of small repairs, it may be preferable to allow some minor acceptable discontinuities to remain in place. Visual inspection is generally adequate for these discontinuities, however MT or PT may be used to supplement visual inspection in unusual situations. Caution should be used with PT, because the dye and developer may cause weld discontinuities if not completely removed before the continuation of welding. Elevated steel temperatures may also reduce the effectiveness of PT. If the weld joint is properly prepared for welding, accessibility is usually sufficient for cleaning using cleaner, cloths, and brushes. Prior to welding, the surfaces are expected to be cleaned in conformance with 5.11.1. Repair welding, following an approved WPS, is then performed to provide an acceptable weld.

C-5.7.2.4 Cracks in Weld or Base Metal. It is imperative that all of the crack be removed. An additional 50 mm [2 in] of weld or base metal is removed at each end of the crack to be sure that the entire crack is removed, because the actual tip of the crack may be hard to determine, and very tight cracks may extend beyond what is visible or detectable with NDT. Good lighting is essential and magnification may be used. Because it does not contaminate the joint and may be used at elevated temperatures, MT is generally the best supplement to visual inspection to be sure that all of the crack is removed, but PT or other NDT methods may be used.

Crack excavations should have a contour and profile that is suitable to provide the joint preparation for repair welding. In cross section, the excavation should have a minimum root radius of 6 mm [1/4 in] and the sides should each be beveled back 15° minimum. In longitudinal section, the excavation should be sloped to the surface at each end with a 45° minimum slope.

Prior to welding, the surfaces are expected to be cleaned in conformance with 5.11.1. Repair welding, following an approved WPS, is then performed to provide an acceptable weld.

C-5.7.4 The Engineer's approval is required before certain types of repairs to base metal and welds can be initiated. These conditions are potentially more serious than routine repairs, therefore careful planning in preparation for repair welding is needed.

All repairs to base metal, other than those edge discontinuities described in 5.2, require the Engineer's approval, providing notice of unusual discontinuities in the base metal or lamellar tearing. Internal discontinuities in ESW and EGW joints usually require more extensive repairs than surface discontinuities or buried discontinuities in welds made by other processes, in part because ESW and EGW processes are usually used in thicker materials. The weld repair may, under unusual conditions, exacerbate grain boundary fissuring or cause the coalescence of small grain boundary cracks that already exist. ESW and EGW joints are also more difficult to accurately evaluate by UT. When necessary to revise the design to compensate for weld or base metal deficiencies, the Engineer is to be notified and approve the proposed redesign, reinforcement, or repair method.

C-5.7.5 Cutting apart of completed welds in completely assembled and welded pieces may damage the material that is to remain. The Engineer is to be notified prior to cutting apart welded joints and attachments so that the structural integrity of the framing can be checked, enabling the Engineer to work with the Contractor to ensure that the problem does not reoccur.

C-5.7.6 If a defective weld or other defective condition is made inaccessible by subsequent work, it may be necessary to take the member apart so that the defective condition can be properly repaired. The Engineer approves the procedure for disassembly and repair. If preferable to change the design to compensate for the deficiency, the Engineer first approves the revised design and repair procedure.

C-5.7.7 Welded Restoration of Material with Mislocated Holes. Fatigue cracks and fractures have initiated in improperly repaired, or disguised, mislocated rivet and bolt holes. When possible, the best repair is to leave the hole open or to fill it with a high-strength bolt. Pretensioning of the high-strength bolt, with washers under the bolt head and nut if needed, may help to restore the buckling strength of compression elements or extend the fatigue life around holes in some tension members. Mislocated holes can be successfully repaired by welding if the provisions of this subclause are followed, but repair of holes by welding is time-consuming and difficult.

Preparing the hole to provide access, welding longitudinal rather than circular beads, and UT or RT can reduce the risk of inclusions. An effective way to repair a hole by welding is to make an elongated excavation to allow good fusion throughout the full length and cross section of the repair weld, then weld using stringer bead techniques. Temporary steel backing may be placed within the hole to support the first side weld. After the first side weld is completed and before welding the second side, the root should be gouged to sound weld metal. Finishing the surfaces flush is also important to reduce stress raisers.

C-5.7.7.1 Statically loaded tension members, and compression members whether subjected to static or dynamic loads, may have mislocated holes repaired under certain restrictions. A special repair WPS is to be followed, and UT or RT of the completed repair, as required by the Engineer, is performed.

C-5.7.7.2 When base metal is subject to dynamic tensile stress, fatigue crack initiation and growth is more likely if the repair is improperly performed, and therefore more care is necessary in the repair of mislocated holes. The Engineer is notified for approval of both the repair method and the repair WPS. Weld quality is verified by either UT or RT, whichever is specified in the contract documents for other tension groove welds, or by the Engineer for the repair.

C-5.7.7.3 When mislocated holes in quenched and tempered steels are to be repaired by welding, these additional provisions apply:

(1) Welding is done with filler metals and a repair WPS that will produce weld metal with appropriate mechanical properties, without adversely affecting the mechanical properties of the base metal.

(2) The Contractor prepares test samples using the repair WPS before making repairs to the structure.

(3) The quality of the test samples satisfies the RT quality requirements for welds subjected to tensile stress. RT is required, without UT as an option, because RT gives excellent results and produces a permanent record. The Engineer may also require UT in addition to RT [see 5.7.7.2(2)].

(4) Mechanical tests are performed to verify that the repair welds will be sound and that the weld metal, HAZ, and base metal will have satisfactory mechanical properties. The minimum mechanical properties of the tested material are the same as the properties for the steel specified.

C-5.8 Peening

C-5.8.1 Peening is the mechanical working of a weld surface by hammering with an appropriate peening tool to create a compressive stress at the surface. Peening is not required for ordinary welds, but is generally reserved for repair welding or highly restrained joints. The Engineer can approve the use of peening which, when properly controlled, may reduce the risk of cracking or lamellar tearing and extend fatigue life. Peening stretches the metal surface, and because the surface is mechanically elongated, the residual stress at that location changes from tension to compression. Since cracks do not initiate or propagate in the absence of tensile stress, cracking is prevented or delayed until a tensile stress from subsequent welding or applied loading overcomes the residual compressive stress.

Peening should be done with a blunt, round tool that will not nick or tear the surface. A 6 mm [1/4 in] radius on the tool is required unless otherwise approved. When this peening tool is used, peening impressions appear similar to large Brinell hardness impressions in soft steel.

Peening energy should not be directed against the fusion boundary or the base metal when using this tool. Base metal is not generally peened, as its surface may be damaged and not subsequently reconditioned by a welding bead. The weld metal is more homogeneous (isotropic) than the base metal and generally has greater toughness and ductility. Because of surface profile, only convex weld metal surfaces should be peened. The root and final layers should not be peened because of the adverse effect of the indentations that may remain. The adverse effect of indentations are not a concern in intermediate weld passes because the layer is remelted and reheat-treated by subsequent weld passes. In addition, root passes are not to be peened because they may crack.

Peening should be done only at temperatures between 65°C and 260°C [150°F – 500°F]. Higher temperatures may damage the steel and cause cracking because of reduced ductility at temperatures in the "blue brittle" range. Effective peening may be done at much higher forging temperatures but there is no provision for such treatment in this code.

All peening equipment needs to operate without contaminating the joint with oil, moisture, or other materials that will interfere with the continuation of welding. When it is suspected that peening has contaminated joint surfaces, the joint should be thoroughly cleaned before the continuation of welding.

C-5.8.2 Use of general weld cleaning hammers, needle guns, and tools, including pneumatic and other impact tools used to remove weld slag, is not considered peening. Peening should only be done using equipment approved for that purpose and when part of an approved WPS.

C-5.9 Caulking

Caulking of welds consists of hammering of the weld or adjacent base metal surfaces to close and hide cracks, porosity, laminations, and other discontinuities in the surface, and is prohibited.

C-5.10 Arc Strikes

An arc strike may be a weld slash across the steel surface or an aborted arc start. Arc strikes may also occur at grounding locations when clamps are not properly installed. Arc strikes result in heating and very rapid cooling. When located outside the intended weld area, these may result in hardening or localized cracking, and may serve as potential sites for initiating fracture. Arc strikes may produce surface discontinuities and hard HAZs.

All welding allowed by the code is based upon stable welding conditions designed to produce sound fusion and a uniform heat input. Arc strikes may produce little if any fusion and have low heat input that is extremely variable. Arc strikes, including their HAZ, may be removed by shallow grinding or machining when the arc strike will not be completely remelted by a subsequent weld pass.

The HAZ below an arc strike may be considered a potential crack source if excessively hard. Cracks, if found, require further exploration and repair. The yoke method of MT is recommended for this purpose because it is easier to perform and causes no arcing of the magnetizing current at the surface. Hardness tests may be performed using simple center punch comparators. When hardnesses are Rockwell C 30 or lower, hydrogen-induced cracking is very unlikely. However, some steels have higher hardness prior to welding, in which case HAZ hardness is limited to the hardness of unaffected base metal. When the HAZ of the arc strike region has unacceptably high hardness, removal of the shallow HAZ below the arc strike should be performed. Grinding to a depth of 3 mm [1/8 in] below the original surface should remove all traces of arc strikes and their HAZs.

C-5.11 Weld Cleaning

C-5.11.1 In-Process Cleaning. Welding should never be attempted through slag or other fused residue from previous weld passes. Attempts to weld through slag and similar deposits may cause fusion discontinuities. As an exception, plug and slot welding may be done by WPSs that keep the weld slag molten until the weld is complete. All welding is to be conducted on surfaces satisfying 5.2. Cleaning by pneumatic or hand chipping hammer, with wire brushing, is usually adequate.

C-5.11.2 Cleaning of Completed Welds. Weld slag, loose or large spatter, and other residue deposits interfere with final weld inspection and may cause coating systems to fail prematurely. All such weld-related residue should be removed at the completion of welding by the welder. In reasonable amounts, small tight spatter may remain unless it interferes with weld testing or painting. Large amounts of weld spatter, even though tight, indicate that the weld process may not have been properly controlled, and such problems should be investigated and corrected. Painting should not be done until final weld inspection is complete and the welds and all necessary repairs are accepted.

C-5.12 Weld Termination

C-5.12.1 Because of the mechanism of starting and stopping the arc, the termination, start, or stop of a groove weld tends to have more discontinuities than are generally found elsewhere in the weld. Therefore, it is best to start and end welds on temporary extensions that can be later removed so that when the temporary extensions are removed, the start-stop discontinuities are also removed. Weld tabs, also called run-off tabs or extension bars, also help maintain the full cross section of the weld throughout its specified length. Weld tabs are installed in a manner that will prevent cracks from forming in the area where the weld tab is joined to the member.

When weld tabs are not used, procedures need to produce sound welds at any starts and stops on permanent material.

Whenever possible, or whenever it is not impossible or impractical, weld tabs should be used. Typical exceptions in bridge construction include stiffener welds, connection plates, and welded gusset plates welded to webs or flanges. In automatic SAW stiffener welding, it is harder to produce a good weld stop than it is to produce a good weld start. To overcome this problem, many operators of opposed-head welders start the weld near one flange and then weld about half of the stiffener length where they temporarily stop the weld. Welding is then resumed near the opposite flange and continued until it intercepts and remelts the initial weld. The welding equipment may be unable to weld to the end of stiffeners, in which case the ends are usually finished using another process.

In other arc WPSs, the welder starts the arc and establishes a weld pool of the required size before proceeding. At the stop location, the travel direction is reversed and the travel speed is temporarily decreased to fill the weld crater before extinguishing the arc. On automatic equipment, this can be accomplished by reversing the travel direction at the weld end while simultaneously increasing the travel speed and then shutting off the power.

Extra care should be given to the inspection of all starts and stops for crater cracks.

C-5.12.2 Weld Tabs. Weld tabs are temporary weld extensions. The toughness of the base metal in the weld tab has no effect because they are removed after welding. There is little dilution of the weld metal with the weld tab steel in the region of the finished weld.

C-5.12.4 The ends of butt joints are to be finished so that there will be no discontinuity in the edge of the finished member that could concentrate stress and reduce fatigue life. The width of the weld and part are not to be reduced more than 3 mm [1/8 in] less than the actual width, or the specified width, whichever is greater. Reinforcement remaining above the surface should not exceed 3 mm [1/8 in]. The slope along the edge of the butt joint, where needed, should not exceed 1:10. No surface roughness values are applicable.

C-5.13 Weld Backing

C-5.13.1 Steel backing acts as a part of the weld and may, to a limited extent, influence the chemical composition and mechanical properties of the weld. AASHTO M 270M/M 270 (ASTM A709/A709M) Grade 250 [36] steel bars may be used as backing for almost all welds Toughness is not specified for backing not larger than 10 mm by 30 mm [3/8 in by 1-1/4 in] because small backing should not affect the fracture characteristics of the member.

C-5.13.2 CJP groove welds made from one side on steel backing require complete fusion of the weld metal with joint faces and the backing. Groove welds made with steel backing have the backing as an integral part of the weld joint. Any discontinuity in the backing perpendicular to significant residual or applied tensile stress may cause the weld to crack at the stress concentration caused by the discontinuity. Only continuous steel backing is allowed by the code, so backing composed of segments is joined by CJP welds, and the soundness of those welds verified, before the backing is installed. A tightly fitted, but unwelded, square butt joint in steel backing constitutes a severe notch that potentially leads to transverse cracks in the weld that can propagate into the base metal. Once the weld is fused to the backing, the backing becomes part of the weld and is affected by residual and applied stress patterns.

C-5.13.3 Steel backing creates stress concentrations in the root, normal to the axis of the weld. When backing is transverse to applied tensile stress, welds with such backing may be subject to fatigue cracking. When backing is parallel to applied stress, there is no appreciable reduction in fatigue life. Backing transverse to computed stress requires removal to avoid or reduce stress concentrations, except in T-joints and columns (see 5.13.3.1). Computed stress, in this application, is both tension and compression stress. Fatigue cracks can grow in compression members when localized plastic deformations at stress concentrations produce tensile stresses as the member rebounds elastically between cycles of increased compression stress. Longitudinal backing is allowed to remain because research has found that it has no adverse effect on performance. When the contract documents specify removal, fused backing is removed, usually by arc gouging and machining, requiring care to avoid damaging base metal. Backing can be a site for corrosion. It is almost impossible to remove longitudinal backing from the inside of box members that are not large enough to accommodate a welder. Removal of longitudinal backing, if not done properly, may cause discontinuities.

C-5.13.3.1 When backing is in a T-joint and is subject only to compressive stresses, such as a column that carries only compressive loads, it may remain in place unless otherwise specified by the Engineer. Backing in butt and corner joints, except in compression areas, is to be removed in conformance with 5.13.3.

C-5.13.3.2 When the backing bar is attached to the steel with external welds, or welds not within the completed welded joint, the weld attaching the backing bar is made continuous full length and meets all requirements of the code. Intermittent welds would serve as fatigue fracture initiation sites and are prohibited for this purpose.

C-5.13.4 These thicknesses are considered the minimum thickness to avoid burn-through for the given process. This assumes that the joint and the backing are assembled correctly. Smaller thicknesses may be used for the processes shown when small electrodes or other factors allow the welding process to be operated with a mid-range heat input. Low heat input welds are not desirable and should not be used to facilitate the use of thin backing.

C-5.13.5 If backing does not fit tightly for the full length of the joint, it is difficult to produce sound welds and much more difficult to perform accurate UT. Loose weld backing escalates repair welding and testing costs. Because of flux and weld metal leakage at the interface of the base metal and a poorly fitting backing bar, porosity and slag may occur with subsequent failure to pass NDT quality criteria.

C-5.13.6 It may be necessary to make root passes from the outside of box members and columns that do not allow access to the back of the weld. For this reason, alternative materials to steel backing are allowed. Any backing material proposed, except steel backing or weld metal deposited by code-approved SMAW electrodes or an approved low-hydrogen WPS, is to be qualified by test in conformance with the provisions of 7.7. A highly skilled welder with proper training is necessary when using nonsteel backing. Copper backing is not permitted if it may be contacted by the welding arc and melted into the weld pool because copper in the weld or HAZ can cause severe cracking. Qualification of water-cooled copper shoes may be considered if the possibility of copper melting is avoided.

Figure C-5.2 These details illustrate assembly tolerances using simple joint details and are not intended to represent recommended details of welded joints. Single V-groove details create more angular distortion when parts are free to rotate. Balanced two-sided weld designs are recommended when there is in-position access for welding on both sides of the joint.

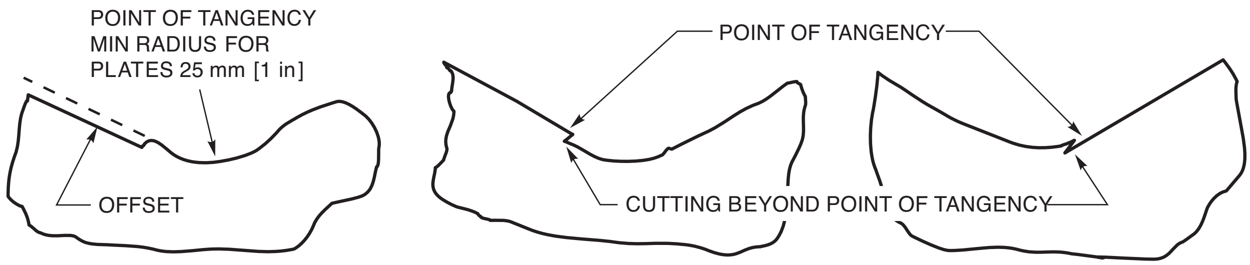


Figure C-5.1—Examples of Unacceptable Reentrant Corners

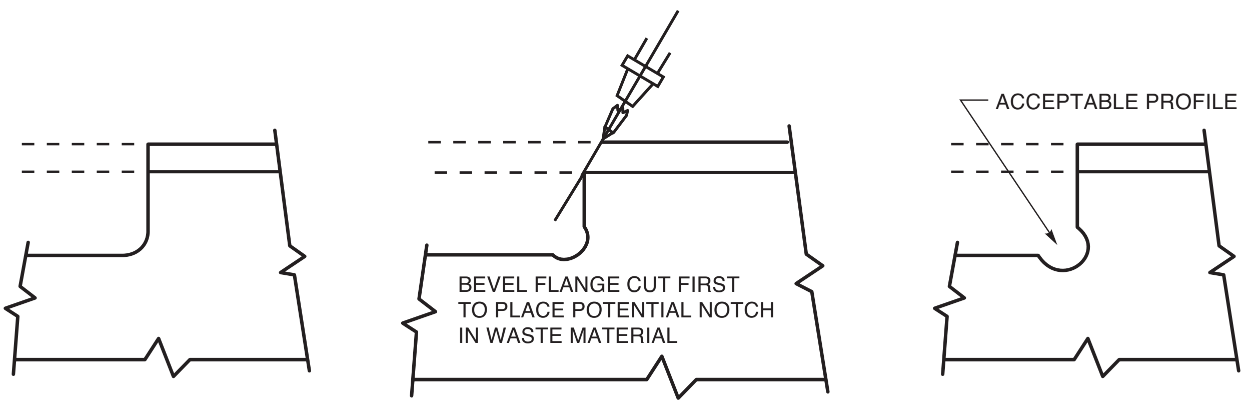
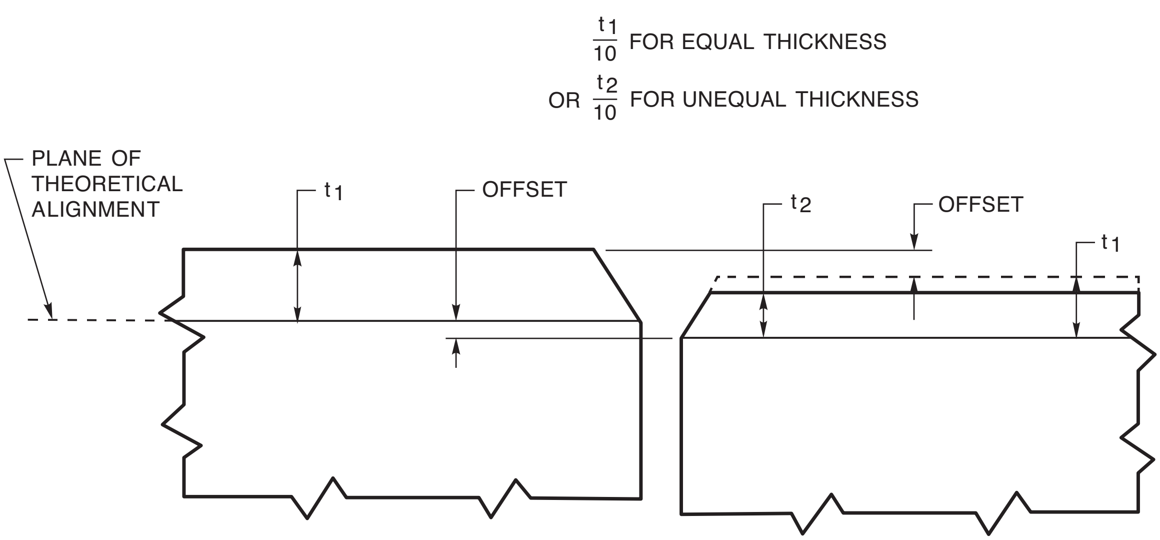


Figure C-5.2—Examples of Good Practice for Cutting Copes



Note: An offset not exceeding 10% of the thickness of the thinner part joined, but in no case more than 3 mm [1/8 in], may be permitted as a departure from the theoretical alignment.

Figure C-5.3—Permissible Offset in Abutting Members (see 5.3.3)

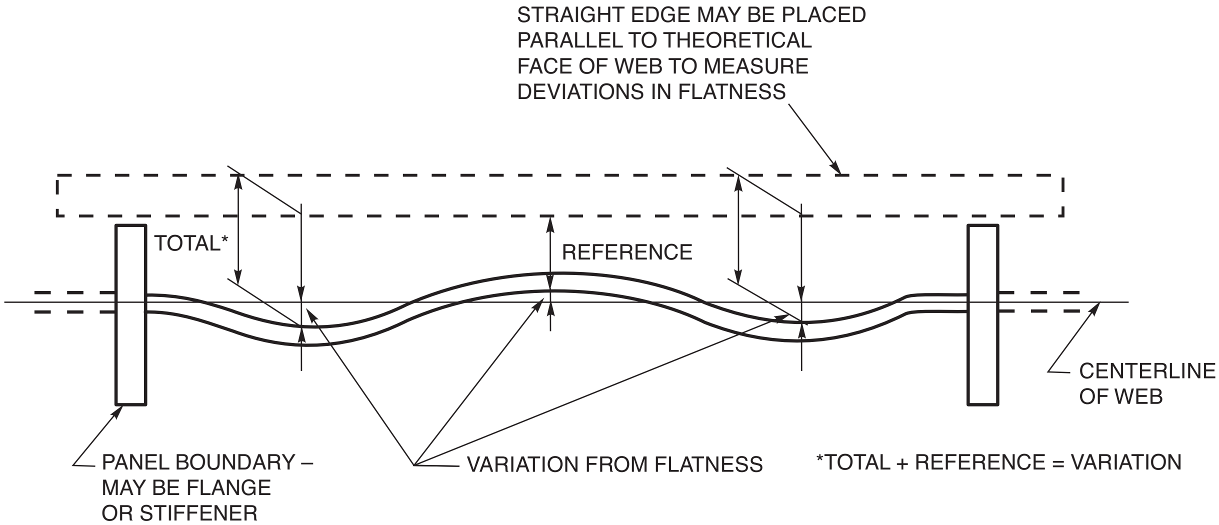
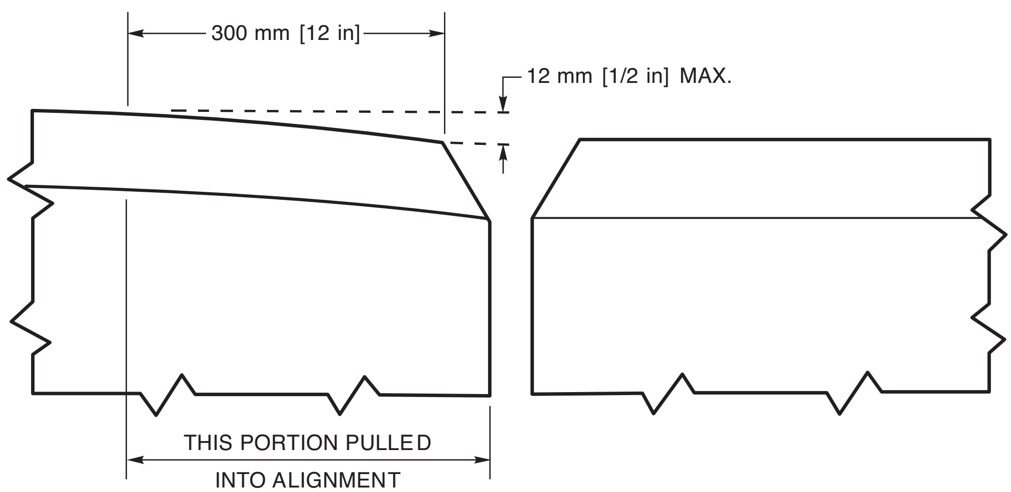
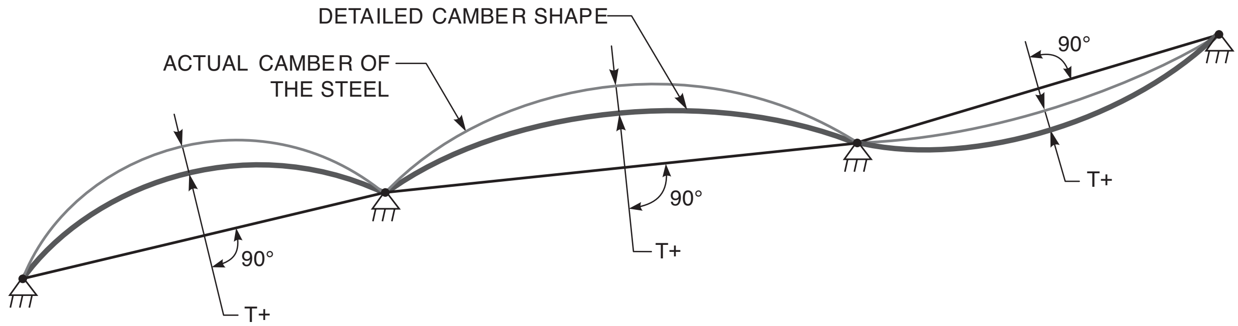


Figure C-5.4—Typical Method to Determine Variations in Girder Web Flatness (see C-5.5.6)



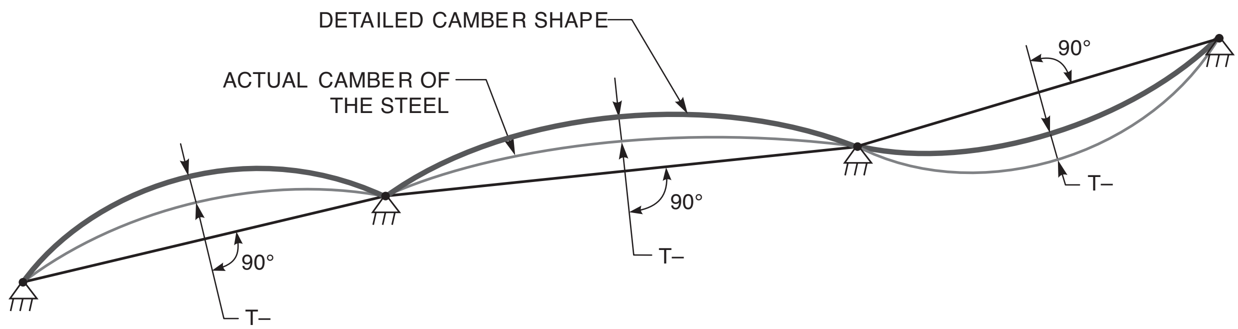
Note: In correcting misalignment that exceeds the permissible allowance, the parts should be drawn to a slope greater than 12 mm in 300 mm [1/2 inch in 12 inches].

Figure C-5.5—Correction of Misaligned Members (see 5.3.3)



PLUS CAMBER TOLERANCE (T+) APPLIES WHEN THE ACTUAL CAMBER OF THE STEEL IS ABOVE THE DETAILED CAMBER SHAPE. THIS TOLERANCE IS MEASURED PERPENDICULAR TO A STRAIGHT LINE BETWEEN THE SUPPORTS OF EACH SPAN.

(A) PLUS CAMBER TOLERANCE



MINUS CAMBER TOLERANCE (T–) APPLIES WHEN THE ACTUAL CAMBER OF THE STEEL IS BELOW THE DETAILED CAMBER SHAPE. THIS TOLERANCE IS MEASURED PERPENDICULAR TO A STRAIGHT LINE BETWEEN THE SUPPORTS OF EACH SPAN.

(B) MINUS CAMBER TOLERANCE

Figure C-5.6—Illustration of Camber Tolerances for Steel Beams

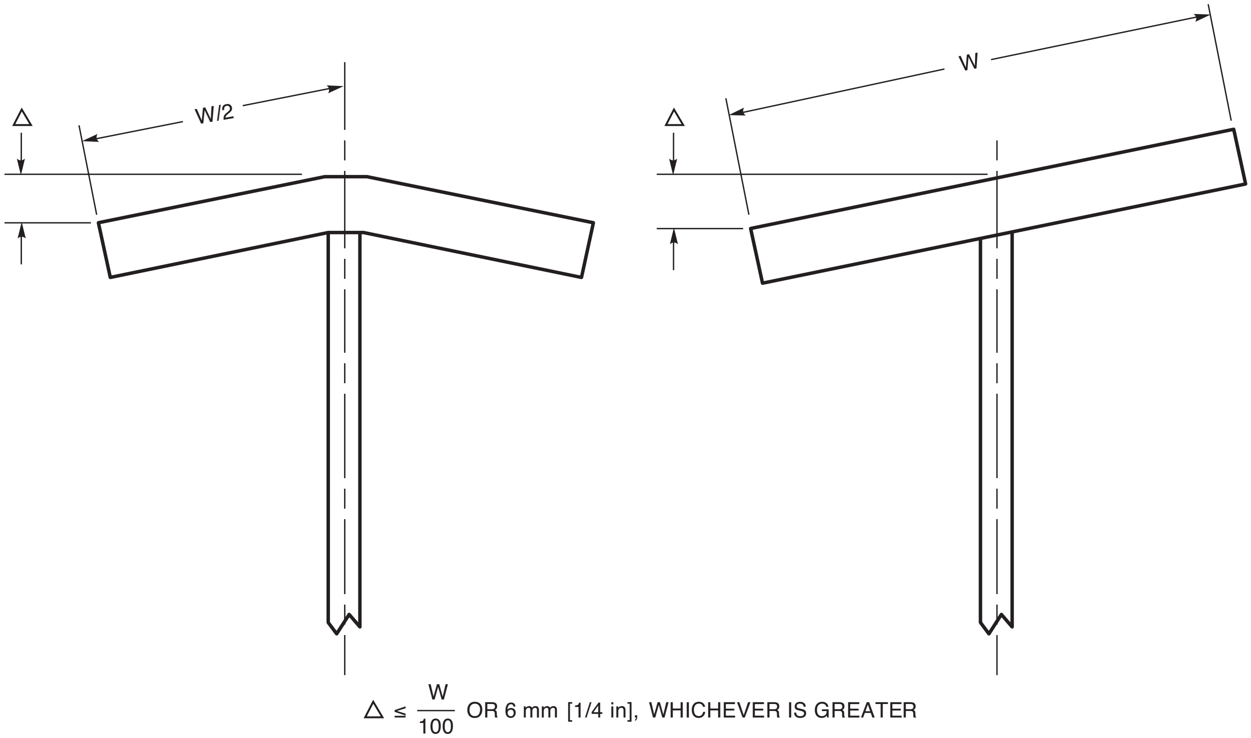


Figure C-5.7—Measurement of Flange Warpage and Tilt (see C-5.5.7)

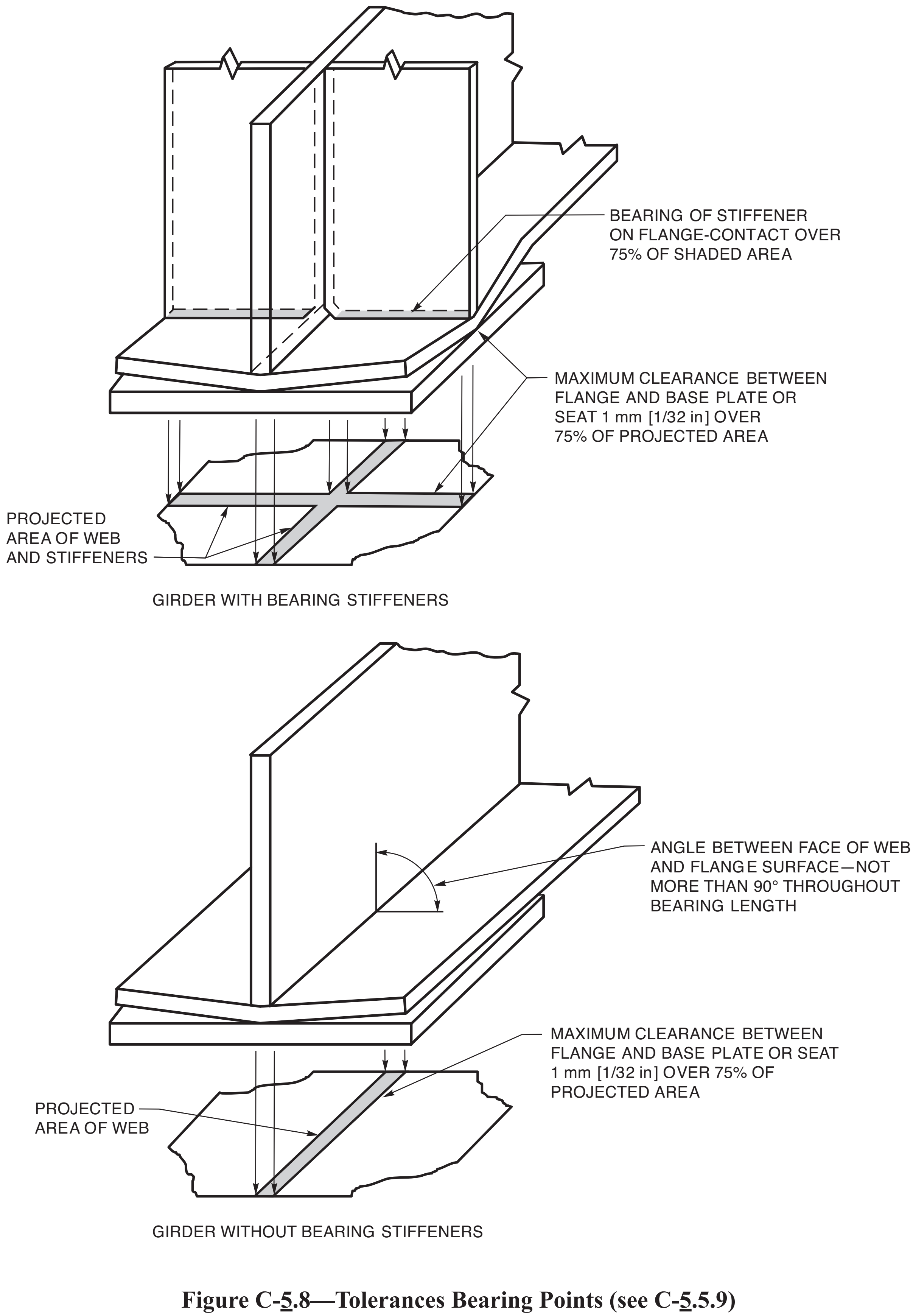


Figure C-5.8—Tolerances Bearing Points (see C-5.5.9)

C-6. Technique.

Current, voltage, travel speed, and placement of individual weld passes in weld preparations of various contours determine the final weld bead volume, shape, and depth. Slightly convex weld bead surfaces are preferred to concave weld surfaces to avoid weld cracking, particularly in root passes of highly restrained joints. Slight concavity is acceptable in intermediate groove weld passes. Excessive concavity is not permitted, as it promotes weld face cracking caused by shrinkage stresses across the face.

Part A
General Requirements

C-6.1 Filler Metal Requirements

Filler metal is defined in Clause 3 as "The metal or alloy to be added in making a welded, brazed, or soldered joint." Weld metal is defined in AWS A3.0M/A3.0, *Standard Welding Terms and Definitions*, as "The portion of a fusion weld that has been completely melted during welding." These terms, filler metal and weld metal, have incorrectly been used interchangeably in practice, and care should be taken to clarify their application. Filler metal is the electrode, as provided under the AWS A5.XX specifications. Weld metal is the product of both filler metal and base metal, mixed as a result of welding in accordance with the provisions of a welding procedure specification, or WPS.

To classify filler metals, welds are made under specific conditions governed by the AWS A5.XX specifications. Prescribed mechanical and chemical tests are performed on such welds and are used to determine the filler metal classification. Weld metal properties are dependent on the specific welding parameters used and the parameters used in production may be different than those used for the filler metal classification tests. To determine the properties of welds that are representative of the welding during bridge construction, a weld is made in conformance with 7.12 and the mechanical properties measured from that weld.

C-6.1.1 Matching Filler Metal. Table 6.1 lists the filler metal specification classifications that are expected to produce welds with mechanical properties that equal or exceed the minimum specified strength, ductility, and toughness of the base metal. Whenever matching filler metal is required, the filler metals are required to be selected from Table 6.1, unless otherwise provided by the Engineer. Undermatching weld metal is required to use electrodes listed in Table 6.1, even though they will not be used on steels with which they are listed. Matching weld metal is required to use filler metals corresponding to the specific grade of steel shown in Table 6.1.

In most cases, using filler metal matching the lower strength material is appropriate because the lower-strength side of the joint will govern. However, for unusual geometries, such as thinner higher-strength material connecting to thicker lower-strength material, the Engineer may need to specify the use of the higher strength filler metal. For example, in a butt joint in which one side is Gr. HPS 70W, 50 mm [2 in] thick, and the other side is Gr. 50, 75 mm [3 in] thick, the weld would be only 50 mm [2 in] thick Gr. 50, thus weaker than both sides of the base metal.

C-6.1.2.1 Based on research conducted on HPS 485W [HPS 70W] and HPS 690W [HPS 100W] by the High Performance Steel Steering Committee and Welding Advisory Group under a cooperative agreement sponsored by the Federal Highway Administration (FHWA), the U.S. Navy, and the American Iron and Steel Institute (AISI), a maximum diffusible hydrogen content of 8 mL/100 g and the preheat and interpass temperature requirements of Table 6.3 were adequate to produce crack resistant weld deposits. A diffusible hydrogen content greater than 8 mL/100 g with various heat inputs produced varying results that could possibly affect the weld quality of these higher strength materials, although not necessarily limited to HPS material.

Therefore, the consensus of the HPS Welding Advisory Group was to propose a requirement for a maximum diffusible hydrogen content of the welding consumables to be 8 mL/100 g for use with conventional, nonfracture critical components to avoid the potential for cracking of these high strength materials when using the existing preheat requirements of Table 6.3 of this code.

Solid electrodes for GMAW are typically not tested for diffusible hydrogen since these electrodes routinely deposit weld metal that is less than H4 levels. Solid GMAW electrodes do not absorb moisture. There are sources of hydrogen beyond the contributions from the electrode; other provisions of this code deal with those issues.

C-6.1.3 Consumable Requirements. This provision makes a distinction between the requirements for consumables used in producing the final product and those used for welding procedure qualification. The procedure qualification consumables do not need to either come from an approved lot or be produced under a quality management program as those welds will not be in the final product.

C-6.1.3.1 Consumable Manufacturer Quality Assurance Program. Filler metal manufacturers that produce filler metal products under a continuing quality assurance program, audited and approved by one or more of the agencies described in 6.1.3.1, have proven that their quality is consistent, and may provide standard products that are not required to be heat or lot tested. Certified copies of conformance by the auditing agency are adequate to verify conformance with this subclause.

C-6.1.3.2 Heat or Lot Testing. The heat or lot testing provides an alternative for consumable manufacturers who do not employ an accepted QA method for consumable quality. This alternative is based on use of the consumables manufacturer's annual AWS A5.XX classification tests. These tests are specified in detail in the AWS filler metal specification series designated A5.XX. The tests required by the A5 specifications, performed by the filler metal manufacturer, are designed to allow classification of, and to demonstrate the capability of, the various consumables to produce sound welds with the required mechanical properties when welding is done under the specified test conditions. Filler metals are tested using specific, uniform procedures so that the results of common tests can be compared.

Under this approach, the Contractor provides certified copies of all pertinent test reports to show evidence that the electrodes furnished conform with all provisions of the AWS filler metal specifications and, where applicable, the FCP. Accepted heats and lots of welding consumables that conform to the same specification and are made by the same manufacturer may be interchanged without concern that different combinations will adversely affect the quality of the weld metal produced. Under heat and lot testing, for example, a specific heat or lot of SAW electrode need not be tested with the specific lot of SAW flux that will be used in production welding, provided the electrode and flux are each from tested heats or lots and meet all other requirements of this code.

C-6.1.4.8 If the contracting authority, usually the Owner, maintains a list of approved manufacturers' brands of electrodes that have been tested with satisfactory results within the past year, it is not necessary for the Contractor to submit certifications for all electrodes used in the work, provided they are of a manufacturer's brand appearing on the list. This system of record keeping reduces duplication of effort at shops, projects, and Owner facilities. The Contractor should maintain copies of all certifications for review by the QA Inspector if requested.

C-6.1.5 Storage. Proper storage of electrodes and fluxes is required because they may absorb or adsorb moisture from the atmosphere or be contaminated by jobsite conditions that may adversely affect weld quality.

C-6.1.6 When used to join bare, unpainted M 270M/M 270 (A709/A709M) Gr. 345W and Gr. HPS 345W steel, the filler metal and weld metal must have mechanical properties suitable to match the base metal, and also must not corrode at unacceptable rates. Although the corrosion rate of weld metal is significantly less than base metal due to much finer grain size in the weld nugget, this code only stipulates the chemical composition when welding corrosion resistant base metals. Since all corrosion initiates at a surface, it is necessary to protect only the weld surfaces with a weld metal that has a corrosion resistant chemical composition. Electrodes used alone or in combination with fluxes or shielding gas to produce a weld with enhanced corrosion resistance are listed in Table 6.2 for this grade steel.

Filler metals with enhanced corrosion resistance generally have increased percentages of nickel, chromium, or copper. These elements may be present alone or in combination with other corrosion resistant elements. Alloy filler metal with enhanced corrosion resistance is more expensive and sometimes more difficult to use than noncorrosion resistant filler metals. When final weld passes can be deposited with corrosion resistant alloy filler metal, making all but the final layers using carbon steel electrodes is permitted. However, all surfaces, including the ends and edges, of a multipass weld must have a cover of at least two layers of corrosion resistant weld metal, so it may be inefficient to switch filler metals and WPSs. It may also be impractical to switch filler metals when making CJP groove welds using weld tabs because the removal of the weld tabs would expose weld passes using nonweathering filler metals. It may be more prudent and less costly to make the entire weld using a corrosion resistant filler metal.

The percentage by weight of specific elements or the combinations of elements necessary to reduce corrosion to an acceptable rate depends on the application. The chemical composition of the filler metals produced by the various electrodes and fluxes is listed in the applicable AWS A5.XX specifications. Table 6.2 only provides for the welding of 345W [50W] and HPS 345W [HPS 50W] steels. Other base metals, including HPS 485W [HPS 70W] and HPS 690W [HPS 100W] steels, also have enhanced corrosion resistance. The filler metal to be used in joining these higher strength steels, when used in the bare unpainted condition, should be selected based upon corrosion resistance and whether matching or undermatching properties are appropriate for the application. Filler metal for weathering steel applications not covered by Table 6.2 must be approved by the Engineer.

The filler metals listed in Table 6.2 for matching steels with minimum specified yield strength of 345 MPa [50 ksi] are of 552 MPa [80 ksi] strength classification, rather than the 70 ksi classification usually used for these steels. This is because the alloying added for atmospheric corrosion resistance also increase the tensile strength of the weld metal, not because additional strength is required.

C-6.1.7 Single Pass Welds for Weathering Steel. This exception to the requirement for corrosion resistant filler metal is permitted for single pass welds or single pass welds on each side because sufficient corrosion resistance will be obtained from dilution with the base metal.

C-6.1.7.1 Shielded Metal Arc Welding (SMAW). SMAW welds no larger than 6 mm [1/4 in] in size may be done in a single pass and should acquire sufficient corrosion resistant elements from the base metal to protect the weld and provide a reasonable color match in the bare unpainted condition.

C-6.1.7.2 Submerged Arc Welding (SAW). SAW welds have greater penetration than SMAW, obtaining more corrosion resistant elements by dilution, and therefore satisfy the weathering requirements for single pass welds to 8 mm [5/16 in].

C-6.1.7.3 Gas Metal Arc Welding (GMAW). GMAW welds have greater penetration than SMAW, obtaining more corrosion resistant elements by dilution, and therefore satisfy the weathering requirements for single pass welds to 8 mm [5/16 in].

C-6.1.7.4 Flux Cored Arc Welding (FCAW). FCAW welds have greater penetration than SMAW, obtaining more corrosion resistant elements by dilution, and therefore satisfy the weathering requirements for single pass welds to 8 mm [5/16 in].

C-6.2 Preheat and Interpass Temperature Requirements

Preheat and interpass temperatures are critical to the prevention of weld-related cracking and must not be overlooked or compromised during construction. Preheat is of little or no value if not done prior to welding in a way that has the steel at the desired temperature when welding begins. It is necessary only to have the steel reach the required preheat at least 75 mm [3 in] (or as otherwise required by 6.2.1.1) ahead of the arc, to each side of the arc, and through the thickness of the steel. It is not necessary to preheat the entire length of weld prior to welding. As an example, preheating torches may be used ahead of a traveling SAW welding head.

Preheating has numerous beneficial effects:

(1) Preheating raises the temperature of the base metal. Combined with the heat input from the welding arc, the cooling rate in the transformation temperature range is reduced. Slower cooling rates promote transformation to softer, more ductile microstructures like ferrite and pearlite. Conversely, very high cooling rates may cause transformation to harder, more brittle microstructures like untempered lower bainite and martensite.

(2) Preheating prolongs the time the weld and HAZ are at elevated temperatures, increasing the rate at which hydrogen diffuses.

(3) Preheating increases the time that the weld metal is molten allowing gases to escape from the weld without being trapped during solidification as porosity.

(4) Preheating, done properly, dries out the joint just prior to welding. It removes all surface moisture and helps burn away hydrocarbons and other surface contaminants that could contribute to cracking or interfere with weld fusion. The early stages of preheating may cause water to condense on the surface of the steel. This is sometimes reported as "water coming out of the steel," but it is simply water, a byproduct of combustion, condensing on the relatively cold steel. Preheating must precede the welding arc with sufficient lead-time to soak the through-thickness of the steel and to evaporate all moisture from the steel surfaces to be welded.

(5) Preheating expands the base metal prior to welding, in some cases reducing the residual stresses and subsequent distortion that will exist after the welds have cooled to ambient temperature.

(6) Preheating helps reduce the risk of lamellar tearing, generally caused by high stresses induced by shrinking weld metal and reduced through-thickness properties in the steel. The preheat necessary to avoid lamellar tears must be maintained long enough for the weld to uniformly cool to the preheat temperature. Additionally, this aids in diffusing hydrogen. Hydrogen itself does not cause lamellar tearing but may aggravate lamellar tearing tendencies.

The cost of preheat and interpass temperature control, and postheat when needed for unusual cases of high strength steels or high restraint, can avoid substantial expenses in repairs. If failure to preheat does not result in a crack soon after cooling, there is still cause for concern. With hydrogen trapped in the weld or HAZ, cracks can initiate or extend even without the application of additional stress.

Hydrogen-assisted cracking is often called "cold" or delayed cracking because it happens after the weld has cooled down to ambient temperature. Most cracking occurs within the first 48 hours, but on rare occasions, may occur much later. Hydrogen-assisted cracking can be transgranular or intergranular, as hydrogen is not hampered by grain boundaries.

When slowly strained mechanical tests are performed on weld metal that contains significant levels of diffusible hydrogen, the specimen crack surface may contain a "fish eye." At the center of the fish eye is the small discontinuity, acting as the original stress concentration that attracted the hydrogen. Around the discontinuity there is a larger circular crack surface that shows no plastic deformation. The crack surface frequently has a dull silver appearance. Fish eyes up to 6 mm [1/4 in] in diameter are not uncommon. Fish eyes are not weld defects and are only seen on slowly strained fractured surfaces.

Diffusible hydrogen migrates toward portions of the steel that are subject to yield point stresses or plastic strains and also toward weld discontinuities where stress is concentrated. When the weld metal or HAZ becomes saturated with hydrogen at a stress concentration, a crack forms and "pops-in." After pop-in, a very small, localized brittle fracture rapidly occurs, and the crack arrests in the weld metal. If stress application continues, more hydrogen migrates to the small area of plastic deformation near the arrested crack and the process repeats itself.

Hydrogen-assisted cracks are commonly believed to have four major prerequisites: (1) a susceptible "hard" microstructure, generally considered as a surface hardness of Rockwell C35 or higher, (2) a sufficient applied or residual stress, (3) diffusible hydrogen, and (4) steel temperature below 200°C [400°F]. The extent of the required prerequisites in each category necessary to cause cracking depends on the conditions that prevail in the total system. If the microstructure is very hard and brittle and the stress is high, low levels of hydrogen may cause cracking. If the diffusible hydrogen level is high, cracking in lower strength steels and at lower stress levels is possible.

The code uses two methods to avoid hydrogen-assisted cracking. The first method is to avoid excessive hardness in the weld and HAZ. The HAZ usually controls because the chemical composition of base metals makes these more susceptible to excessive hardness. This is done by controlling the preheat, interpass temperature, and welding heat input. High welding heat inputs are very successful in avoiding excessive hardness in carbon and low-alloy steels of moderate thickness.

The second method of avoiding hydrogen-assisted cracking is to minimize the hydrogen entering the weld and HAZ. The use of properly stored and controlled low-hydrogen electrodes and flux, suitable shielding gases, and clean base metal surfaces is required.

Except for FCM repairs in Clause 14, the code does not directly address postheat. However, postheating may also be used to minimize hydrogen-assisted cracking. Postheating requires the steel to be kept at an elevated temperature long enough to permit excessive hydrogen to diffuse from the weld and HAZ before cooling to ambient temperature. The code has provisions for preheat and interpass temperature control, but postheat requirements, if any, are left to the Contractor and the Engineer. Postheating, which generally consists of heating completed welds to 230°C [450°F] and maintaining that temperature for at least one hour for each inch of weld thickness, effectively reduces hydrogen from welds and HAZs. When done properly before the weld is allowed to cool, postheating is very effective in preventing hydrogen-assisted cracks. When weld joints are large, or severely restrained, when high strength steels are to be welded, or when other conditions suggest that hydrogen-assisted cracking could be a problem, postheating may be considered by either the Contractor or the Engineer. See C-12.15.1 for additional information on postheat.

Both preheating temperatures and methods are important. The code requires preheating through the full thickness, or at least 75 mm [3 in] in all directions from the point of welding. This is to ensure that a specified minimum mass of steel is heated to at least the minimum specified temperature. Both the temperature and the mass of steel that is preheated combine to determine the cooling rate and the time above 200°C [400°F]. The more steel that is brought up to temperature in preheating, the better the protection against cracking. Heating significantly above specified preheating temperatures could adversely affect strength and toughness, particularly when welding quenched and tempered (Q&T) steels. A soaking preheat at the specified temperature is better than excessive preheat in small areas.

The effectiveness of preheat may be improved by increasing the area or volume of steel heated. The maximum volume receiving preheat is not limited by code. A soaking preheat to achieve the specified temperature is better than excessive preheat applied to small areas.

C-6.2.1 Minimum Preheat and Interpass Temperature. Automatic stud welding is exempted from preheating because the process has a high welding heat input, and produces a limited weld and HAZ area. ESW and EGW processes have extremely high welding heat inputs and produce very slow cooling rates, and therefore are not subjected to minimum preheat provisions. Tack welds that will be remelted using SAW need not be preheated because the heat of the welding process is adequate to recondition any hardened region below the tack weld.

C-6.2.1.1 Extent of Preheat. The code reflects that preheat must be present, at a minimum, within 75 mm [3 in] of the point of welding, but that it is not necessary to preheat the entire length of the joint before welding begins. For a shorter weld, such as a butt splice on a narrow flange, the fabricator may choose to achieve preheat for the full length of the joint before welding starts. For longer welds, such as web to flange fillet welds, the fabricator may choose to preheat locally as welding proceeds.

Though maximum interpass temperature is measured relatively close to the weld (see 6.2.2), minimum preheat temperature and minimum interpass temperature are measured at least 75 mm [3 in] from the edge of the weld joint to better ensure that the entire volume adjacent to the weld will be at or above the minimum preheat and minimum interpass temperature.

C-6.2.1.2 Annex F Option. The optional methods of calculating preheat temperatures listed in Annex F include both the hardness and hydrogen control methods of avoiding weld and HAZ cracking. Both methods are very conservative; therefore it is unlikely that these provisions will indicate that temperatures lower than those specified in Table 6.3 will be acceptable. If a lower temperature is calculated, the lower temperature cannot be used unless the procedure is qualified using a test acceptable to the Engineer. Qualification using the provisions of 7.12 provides limited assurance of freedom from cracking because the standard qualification test configuration has insufficient size and restraint to produce the intensity of residual stress present in the full-size structure.

The methods provided in Annex F are based on laboratory cracking tests and may predict preheat temperatures higher than the minimum temperatures shown in Table 6.3. The guide may be of value in identifying situations where the risk of cracking is increased due to composition, restraint, hydrogen level, or welding heat input where higher heat input may be warranted. Alternatively, the guide may assist in defining conditions under which hydrogen cracking is unlikely and where the minimum requirements of Table 6.3 may be safely relaxed, based upon WPS qualification testing.

C-6.2.1.3 Based on research conducted on HPS 485W [HPS 70W] by the High Performance Steel Steering Committee and Welding Advisory Group under a cooperative agreement sponsored by the Federal Highway Administration (FHWA), the U.S. Navy, and the American Iron and Steel Institute (AISI), lower preheat and interpass temperatures could be allowed by controlling the filler metal diffusible hydrogen content and minimum and maximum heat inputs. AASHTO adopted these requirements in both the first and second editions of the *Guide Specifications for Highway Bridge Fabrication with HPS 70W Steel*, which has been used as a guide to fabricate and weld numerous bridges in service for several years. These optional requirements and controls are in Annex G.

C-6.2.2 Maximum Preheat and Interpass Temperature. Excessively high preheat and interpass temperatures, when combined with high welding heat inputs, create very slow cooling rates that contribute to large grain size and a resultant lack of toughness in the HAZ. Therefore, for 485 MPa [70 ksi] and 690 MPa [100 ksi] steels, a maximum preheat and interpass temperature is specified.

C-6.2.2.1 Extent of Interpass. Exceeding the maximum interpass temperature is more likely when making multiple pass welds on short joints, such as flange splices. On such joints, caution should be taken to ensure that the weld area will be below the maximum interpass temperature when the weld is made, not only at the start of the pass, but also as the weld progresses. A practical means of ensuring this condition is to measure the temperature of the joint at the end of the previous weld pass; if this point is below the maximum interpass temperature, the whole joint is likely to be below the maximum interpass temperature.

C-6.2.3 Base Metal/Thickness Combinations. When joining steels that fall into different categories of Table 6.3 or Annex F, the highest preheat required for either steel or thickness is required. For example, a Grade 345W [50W] steel of 50 mm [2 in] thickness joined to a Grade HPS 690W [HPS 100W] steel of 30 mm [1-1/4 in] thickness requires a minimum 65°C [150°F] preheat using Table 6.3. A Grade 250 [36] steel of 40 mm [1-1/2 in] thickness joined to a Grade 345 [50] steel of 70 mm [2-3/4 in] thickness requires a minimum preheat of 110°C [225°F].

C-6.2.4 Special Conditions. The minimum preheat temperatures required in Table 6.3 have been adequate when welding steel of average chemical composition and moderate thickness with joints under conditions of moderate restraint. However, higher preheat and interpass temperatures may be necessary to avoid cracking with conditions of high restraint, susceptible steel chemical compositions, low heat input WPSs, or high hydrogen levels. The Contractor must provide adequate preheat and interpass temperature to avoid cracking, even if in excess of the Table 6.3 or Annex F value. However, the maximum temperatures in Table 6.3 (Note a), or in 6.2.2, as applicable, must not be exceeded. Should the weld region experience cracking when using the highest permitted preheat, other means must be taken to avoid cracking.

C-6.2.5 Minimum Ambient Temperature. The code presumes that welding personnel will not consistently produce acceptable results when working in an environment where the temperature is lower than –20°C [0°F]. A heated shelter to protect the welder and the area being welded from inclement conditions may be used. As long as the temperature within this shelter provides an environment of –20°C [0°F] or above, the prohibition of 6.2.5 is not applicable but the Contractor must still ensure weld quality is not adversely affected. The environmental conditions within the shelter do not alter the preheat or interpass temperature requirements for the base metal.

C-6.2.6 Measurement of Minimum Temperature. Temperature indicating crayons, infrared devices, or other equally positive means should be used to measure for preheat or interpass temperature prior to the start of each pass, until completion. When heating with individual heating sources (e.g., “rosebud” multi-orifice torch hand held or mounted on machine), wait at least 3 seconds to 5 seconds after the source leaves the location to permit soak-in and to avoid false readings.

C-6.2.7 Minimum Base Metal Temperature. Cold steel will increase the rate of cooling of the preheat area. Steel below 0°C [32°F] may also hold ice or frost in locations such as weld backing and weld tabs, as well as the surfaces immediately adjacent to the place where the weld will be made. This moisture must be removed prior to the start of welding.

C-6.2.8 Alternate SAW Preheat and Interpass Temperature. Parallel or multiple electrode SAW have high welding heat inputs, adding sufficient heat to the joint as it progresses that advance preheating may not be necessary (see C-6.10.4).

C-6.3 Heat Input Control for Grade HPS 690W [HPS 100W] Steel

The strength and toughness of the HAZ of welds in HPS 690W [HPS 100W] steel is related to the cooling rate. Contrary to the principles applicable to other steels, the fairly rapid dissipation of welding heat is needed to retain adequate strength and toughness for this steel. The cooling rate of an austenitized HAZ must be sufficiently rapid to ensure the reformation of the hardening constituents in the steel microstructure. When Grade HPS 690W [HPS 100W] steel is heated and then followed by slow cooling, this prevents the formation of a hardened microstructure.

Because the maximum heat input for Grade HPS 690W [HPS 100W] steel varies over a wide range, heat input as developed and recommended by the steel manufacturer should be strictly observed. Either the preheat temperature is specified based on welding heat input or the welding heat input is based on the provided preheat and interpass temperature.

One way to improve the toughness of welds on Grade HPS 690W [HPS 100W] steel is to use a multiple pass welding procedure that utilizes less heat input than would be the case if the same size of a weld was made in a single pass. Because of the low heat input, these areas will cool faster and will favor the formation of a finegrained microstructure and improve toughness. The last weld pass should be placed on previously deposited weld metal, not the base metal. Because the weld metal is less hardenable than the base metal, the last weld pass and HAZ should be placed where it will not cause unacceptable hardening. Sometimes, an extra bead will be deposited on top to refine and temper the beads below. The excess reinforcement may be removed by grinding or machining.

C-6.4 Stress Relief Heat Treatment

C-6.4.1 General. Very little stress relief heat treatment is performed in bridge construction because it is not needed in most situations. The use of thermal stress relief is limited by high costs and concern that damage may be done to the product. However, when necessary for special conditions, thermal stress relief is very effective in removing significant residual stresses, regardless of source.

Compared to lighter sections with smaller welds, highly restrained weldments are more likely to crack or tear in the furnace, particularly those made of thick steel with large welds or with steel stressed in the through-thickness between large welds. As stresses are relieved during heat treatment, weldments change shape to some degree. The extent of change depends on the weld size, the original rigidity of the assembly, and the residual stresses in the weldment. Light sections are more likely to sag or lose their shape in the furnace. As temperatures rise, the yield stress of the steel decreases and the parts may sag between supports in the furnace. Temporary support may be necessary.

Heating of Q&T steels to stress relief temperatures may reduce toughness and strength. Stress relief of Q&T steels requires heating to the tempering temperature, close to the transformation temperature range, and therefore should be done with extreme caution so that maximum permitted temperatures will not be exceeded.

All final NDT necessary to assure the soundness of welds, HAZs, or base metal should be done after the heat treated weldments have cooled to ambient temperature. After weldments are removed from a heat treating furnace, they should be carefully inspected, particularly at changes in section and at other locations where stresses may have been concentrated. As stresses are relieved at elevated temperatures, preexisting discontinuities may extend or new discontinuities may form. Because weld repairs performed after heat treatment may necessitate a repeating of the heat treatment, NDT prior to heat treatment should also be considered. Contract documents should clearly state the timing of all required NDT.

C-6.4.2 Requirements

C-6.4.2.2 Rate of Heating. Large furnaces used for stress relief may be subject to temperature variations within the furnace. Several recording pyrometers are routinely used in simultaneous operation to monitor temperatures in various parts of the furnace, with others monitoring the temperature of the steel part in various locations. This is done to ensure that weldments to be given a stress relief heat treatment are heated and cooled uniformly and properly.

Consideration of closed chambers and complex structures may require rates of heating and cooling below those allowed by 6.4.2.2 to avoid structural damage due to excessive thermal gradients.

C-6.4.2.3 Holding Time. Calculations of holding time are specified based on weld size, if performed for stress relief, or the maximum steel thickness, if performed for dimensional stability. The holding time required for a weldment constructed of 100 mm [4 in] thick steel using 25 mm [1 in] groove welds to connect web to flange could be considerably different depending on the purpose for stress relief.

Most of the expense of thermal stress relief is in transportation, getting the weldments positioned in the furnace and bringing the weldment up to the specified temperature at acceptable rates. Once the furnace and charge are at temperature, maintaining that temperature for sufficient time to ensure stress relief has been accomplished adds relatively little extra cost.

C-6.4.2.4 Rate of Cooling. To protect the steel from cooling too rapidly, cooling is specified to be done at controlled rates in the furnace until it reaches 315°C [600°F]. Provided maximum stress relief temperatures are not exceeded, damage to the steels listed in this code should be limited to minor surface oxidation.

C-6.4.3 Alternative PWHT. As treating temperatures are lowered, the stress relief may become less complete. Lower temperature stress relief heat treatments should only be considered when there are special conditions that justify their use. See 12.15 and C-12.15 for more information on PWHT.

Part B
Shielded Metal Arc Welding

C-6.5 Electrodes For SMAW

C-6.5.1 SMAW Electrodes. The choice between carbon steel and low-alloy electrodes depends on the minimum required tensile strength of the weld metal. All SMAW electrodes with a minimum tensile strength of 550 MPa [80 ksi] or greater are furnished as low-alloy steel electrodes under AWS A5.5/A5.5M.

The code requires that all electrodes satisfy low hydrogen requirements. AWS A5.1/A5.1M carbon steel electrodes using the designation E70X5, E70X6, or E70X8 are considered low-hydrogen, with an as-received or conditioned moisture content in the coating of not more than 0.6%. Those with the additional designator R have a moisture content in the coating of not more than 0.3%, and the E7018M electrode has a moisture content of not more than 0.1%. Optional diffusible hydrogen limits may be specified, with designators H16, H8, or H4. These values are commonly used in calculating preheat requirements using Annex F (see Annex F6.2 and Table F.1).

Similar designations are used for AWS A5.5/A5.5M low-alloy electrodes. EXXX5-X, EXXX6-X, and EXXX8-X electrodes are considered low hydrogen. As-received and conditioned moisture content limits vary by classification and electrode strength, with lower moisture levels required for higher strength electrodes. Optional diffusible hydrogen limits may be specified, with designators H16, H8, or H4.

All low-hydrogen SMAW electrodes have an extruded coating of inorganic material. The code only permits the use of those electrodes classified as EXXX6 or EXXX8, using potassium or potassium/iron powder-type coatings, with the exception of one EXXX5 sodium-type electrode for weathering steel. E7016 and E7018 electrodes may be purchased as carbon steel or low-alloy electrodes. Iron powder added to the coating improves arc stability and deposition rates. E7018 electrodes have approximately 30% iron powder, by weight, in the coating and E7028 electrodes have approximately 50%. The higher the percentage of iron powder, the higher the deposition rate. E7028 high deposition rate, iron powder electrodes produce larger molten weld pools covered with a thick coating of slag. These welds take longer to completely solidify and stay hot longer. As a result of being more fluid and having longer cooling times, these electrodes cannot be used for out-of-position welding, and the welds tend to have lower toughness than E7018.

E7018 electrodes generally produce welds with excellent toughness. AWS A5.1/A5.1M E7016-1 and E7018-1 electrodes are also available as a subclassification offering even better toughness than standard E7018 electrodes. These electrodes are essentially the same as other similarly classed electrodes, except the resulting weld metal may have manganese content near the maximum permitted by the filler metal specifications to increase toughness. Electrodes designated E7028 may be purchased only as carbon steel electrodes as they are not available as alloy steel electrodes. All electrodes purchased under the provisions of AWS A5.5/A5.5M are required to have a suffix to identify the chemical composition of the deposited metal.

The difference in permitted maximum moisture content in the coating between the AWS A5.1/A5.1M and AWS A5.5/A5.5M specifications has led some to conclude that when low-hydrogen welding is particularly important, as in the case of repair welding or the fabrication of FCMs, it is better to purchase the electrodes as low-alloy electrodes under the provisions of AWS A5.5/A5.5M. However, low-alloy electrodes are not superior to similar carbon steel electrodes and may be less desirable because of their alloy content.

Most, if not all, modern SMAW low-hydrogen electrodes have a coating moisture of less than 0.2% by weight. The low-hydrogen properties of E70XX electrodes purchased under the provisions of AWS A5.1/A5.1M and AWS A5.5/A5.5M should be equivalent as far as low-moisture content is concerned. Low-hydrogen SMAW electrodes furnished in undamaged hermetically sealed containers should provide acceptable low-hydrogen performance when the containers are opened and the electrodes are used without prolonged exposure to the atmosphere.

Low-hydrogen electrodes require a short arc length to ensure proper operation and effective shielding. Proper welding technique can be verified by observing the quality of the finished welds.

The strength of weld metal produced using SMAW electrodes under the provisions of AWS A5.5/A5.5M is dependent on the alloying elements. The alloy elements used to increase strength in weld metal have varying effects on toughness, weldability, and cost.

Alloy electrodes in the same strength level classification are not equivalent in terms of toughness and resistance to weld cracking because they do not produce welds with the same chemical composition. For this reason, the selection of alloy-type electrodes is limited to specific classifications in Table 6.1. See AWS A5.1/A5.1M and AWS A5.5/A5.5M for details of the required chemical analysis, mechanical test results and the method of electrode classification.

C-6.5.2 Low-Hydrogen Drying Requirements. Drying requirements vary depending on the type of electrode. Care should be taken not to exceed the manufacturer's specified temperature ranges, as damage to the electrode coating may result.

Once removed from undamaged hermetically sealed containers or from drying ovens, SMAW electrodes not issued for use must be placed in a storage oven and held continuously at a temperature of at least 120°C [250°F] until dispensed for use. At that temperature, they will not pick up moisture from the atmosphere. Care should be taken to monitor the proper operating temperature of the storage oven, and to prohibit the introduction of materials other than electrodes into the oven.

C-6.5.2.1 Approved Atmospheric Exposure Periods. Table 6.6 lists the maximum permissible time that electrodes can be exposed to the atmosphere. This table does not apply to those electrodes with an optional supplemental moisture resistance designator "R" for use on steels with minimum specified yield strength of 345 MPa [50 ksi] or lower. See 6.5.2.3 for exposure times for these electrodes. Exposure is based on the strength level of the steel to be welded with the designated electrode, with an assumed relationship between steel strength and electrode used. Higher strength steels can tolerate less hydrogen than lower strength steels. Hydrogen from the welding arc and weld pool contaminates the HAZ, assumed to have a strength equal to or higher than the weld.

How much moisture is absorbed or adsorbed (adheres to the outside but is not absorbed) by electrodes depends on the ambient temperature and humidity and the electrode storage conditions. Electrodes in small, dry containers open only at the top are partially protected, and will pick up considerably less moisture than electrodes lying unprotected on cold, damp steel. Electrodes placed near open flames to "warm" are subject to unusually high rates of moisture pick-up, because a byproduct of combustion is water. Electrodes should never be placed in contact with wet or damp surfaces and should never be stored above the exhaust from gas heaters or in other areas of concentrated moisture. Drying at 230°C to 290°C [450°F to 550°F], when exposure times exceed Table 6.6 limits, restores the electrode coating to satisfactory moisture content only if the electrode has remained essentially dry, but may not be sufficient to avoid weld or HAZ cracking in high strength steels or highly restrained joints. Additional drying is required when welding Grade HPS 690W [HPS 100W] steel (see 6.5.3).

C-6.5.2.2 Short Exposure Times. Electrodes being held during this four-hour period should be identified so that they are not immediately used. Storage ovens should have activity records and segregated storage to verify that electrodes are not prematurely distributed.

C-6.5.2.3 Optional Supplement Moisture-Resistant Designators. In order for a low-hydrogen electrode to be designated as low-moisture-absorbing with the "R" suffix designator, electrodes are tested by exposure to 27°C [80°F] and 80% relative humidity for a period of not less than nine hours. These tests are defined in AWS A5.1/A5.1M and AWS A5.5/A5.5M, and are typically conducted by the electrode manufacturer. The nine hour time period was selected based on a typical workshift length, including mealtime. The moisture content of the exposed covering must exceed the maximum specified moisture content for the "R" designated electrode and classification in the appropriate AWS A5.1/A5.1M or AWS A5.5/A5.5M specification. R-designated E70XX-X, E80XX-X, E90XX-X, E100XX-X, and E110XX-X electrodes may be used with exposure times of up to nine hours on steels with a minimum specified yield strength of 345 MPa [50 ksi]. For other electrodes, exposure time is limited to that permitted in Table 6.6.

C-6.5.3 Electrode Restrictions for Grade HPS 690W [HPS 100W] Steel. This is a requirement even for new electrodes from undamaged hermetically sealed containers with no apparent damage, in case a leak is present.

C-6.5.4 Redrying Electrodes. For electrodes exposed only to atmospheric moisture, but for a period longer than that permitted in Table 6.6, drying at 230°C to 290°C [450°F to 550°F] may restore the electrode coating to satisfactory moisture content. Electrode manufacturers should be consulted for proper drying procedures. Electrodes may be redried only once and should be marked to prevent additional drying cycles. Electrodes that have been wet must not be dried or used because redrying may not sufficiently remove all moisture and the coating may be damaged.

C-6.6 Procedures for SMAW

C-6.6.1 Flat Position. Weld surface contours are better when welding is done in the flat position. Higher welding heat inputs can be used in the flat position, and gravity helps to control the weld bead contour. Higher welding current means higher deposition rates, reducing costs. Less skill is generally required to weld in the flat position, and the number and severity of weld defects should be reduced.

C-6.6.2 Suitability. Low-hydrogen electrodes must be used. These electrodes use a very short arc length, about 2 mm [1/16 in] or less, to properly shield the arc and provide proper welding conditions. SMAW voltage is a function of arc length. Current, also called amperage, is selected for the electrode diameter and welding position. Large electrodes require more current to operate properly. Current and welding speed determine the size of the molten pool. The manufacturer provides a recommended range of welding current for the given electrode and the WPS to be used must fall within this recommended range.

C-6.6.3 Maximum Electrode Diameter. These limitations are based on experience in the control of electrodes under various welding conditions.

(1) 6.4 mm [1/4 in] electrodes are not permitted for welding the root of groove welds because they may burn-through and create weld defects.

(2) 6.4 mm [1/4 in] is the maximum size electrode that can make sound fillet welds in the horizontal position, provided the base metal is thick enough to absorb the welding heat without melting through.

(3) 6.4 mm [1/4 in] electrodes and smaller can be used where gravity will control the weld pool, the base metal and backing can support the welding heat, and there is sufficiently wide access for fusion at the root. This size electrode is not permitted in the root of groove welds made without backing or in square groove welds because it may melt through and create weld defects.

(4) 4.0 mm [5/32 in] electrodes are the largest permitted for welding in the vertical and overhead positions. They produce a manageable weld pool size that solidifies fast enough to prevent sagging, running, or dripping.

(5) 5.0 mm [3/16 in] electrodes are the largest permitted for root passes in groove welds made without backing, for root passes in square groove welds with backing and a root opening less than 6 mm [1/4 in], and for all passes in groove welds made in the horizontal position.

These maximum electrode sizes are based primarily on the standard joint details in Figures 4.4 and 4.5. Smaller electrodes can and often should be used. For CJP joints with backing, the welding electrode including the coating should be able to touch the bottom of the weld joint preparation at the beginning of welding and between each subsequent weld pass. If this cannot be done, the electrode is too large or the joint is improperly prepared. For PJP or CJP joints requiring backgouging, electrode selection should consider joint geometry and final weld quality. If there is insufficient access during welding, the WPS, welding technique, or sequence of weld passes is either incorrect or not being followed properly.

C-6.6.4 Minimum Root Pass Size. The code requires the root pass to be large enough to prevent cracking under the prevailing welding conditions. Larger root passes have more size over which to distribute the shrinkage stress and cool more slowly because of the increased welding heat input. This helps avoid problems with weld and HAZ hardening and hydrogen-assisted cracking.

C-6.6.5 Maximum Root Pass Thickness. Excessively thick root passes are undesirable because uniform fusion to the weld root may not be achieved when thick root passes are made. Additionally, the notch toughness of the root pass region may be reduced since less of the cross section of this pass will benefit from subsequent grain-refining weld passes.

C-6.6.6 Maximum Single-Pass Fillet Weld Size. Large fillet weld sizes may not be able to obtain consistent fusion at the weld root and weld toe. Overlap and poor surface profile may also occur.

C-6.6.7 Maximum Fill Pass Thickness. The maximum layer thickness requirement is a provision to control weld soundness. Excessively thick, and thus large, weld passes are more likely to have fusion defects. The thickness, along with the bead width, are roughly proportional to heat input. Relatively thin weld layers permit generous refinement by subsequent weld passes, improving notch toughness.

C-6.6.8 Vertical Progression. The progression of all weld passes is normally required to be vertical-up to ensure that there is sound fusion and that the welding heat input is sufficient to prevent cracking. However, welding may be done in the vertical-down position if a procedure qualification test is successfully completed and approved by the Engineer.

C-6.6.9 CJP Backgouging. Backgouging weld joints from the opposite side ensures that sound weld metal will be contained throughout the joint. The weld root pass is the most difficult pass to make and may contain fusion defects, slag inclusions, or porosity. Even properly made root passes are backgouged in order to remove the remaining root face. Sound metal in the root of the second side weld is necessary before welding proceeds, and gouged areas are ground to bright metal per 5.2.9, to remove any potential carbon or copper deposits that may remain after gouging.

Part C
Submerged Arc Welding (SAW)

C-6.7 General Requirements

C-6.7.1 SAW Electrodes. The submerged arc welding process has been in use throughout the United States since the 1940s. Submerged arc welding is used for an estimated 90% of the volume of all bridge welds. It is the preferred welding process for bridge construction because of the high quality and the relatively low costs that result from high weld deposition rates. SAW, when used in accordance with a properly qualified WPS, can produce smooth, attractive, defect-free welds with good mechanical properties.

Most submerged arc welds have adequate appearance even when their mechanical properties or soundness may not meet specification requirements. The molten weld pool is protected from the atmosphere and is cleansed by flux that has been melted with the electrode and the base metal in the welding arc. The molten flux floats to the top of the weld pool where it forms a protective slag layer. It solidifies upon cooling and becomes friable so that removal is usually relatively easy after the weld has cooled. The weight of the flux cover, and the fact that the welding is done in the flat or horizontal welding position where gravity helps to shape the weld surface, combine to give all properly made SAW welds a smooth appearance.

Electrodes may be operated DC+, meaning direct current with the electrode positive (reverse polarity); DC–, meaning direct current with the electrode negative (straight polarity); or AC, alternating current. DC+ provides the deepest arc penetration. DC– is used for high deposition rates and low penetration, and is generally best for horizontal position fillet welds. AC deposition rates and penetration are between DC– and DC+. Magnetic fields created around DC welding electrode(s) deflect the arc and result in arc blow, which may hinder or enhance weld fusion, depending on the specific application.

Submerged arc welding may be done by welding with a single electrode, parallel electrodes, or multiple electrodes in tandem. The electrical circuit may consist of combinations of single or parallel electrodes, provided they all feed the same weld pool. Under the provisions of 6.10.3, because GMAW leaves a weld deposit essentially free of slag, GMAW and SAW procedures can be combined even though the GMAW does not feed the same weld pool as the SAW. Single, parallel, and multiple electrodes are defined in Clause 3, Terms and Definitions.

A common method of high deposition SAW employs multiple electrodes in tandem, one single or parallel electrode preceding another in an arrangement parallel to the weld axis. Typically, the leading electrode is a single electrode operated DC+ for good root penetration. The trailing electrode is typically another single electrode operated AC for lateral distribution so that there will be little or no magnetic interference between the two separate arcs.

Parallel electrodes may be substituted for single electrodes. Parallel electrodes can produce higher deposition rates because the two small electrodes melt faster by resistance heating than a large single electrode of equivalent volume. Composite, or tubular, electrodes also can produce higher deposition rates because of their higher melting rates. Both parallel solid and composite single electrodes have lower penetration than equivalent single solid electrodes. Possible drawbacks of using parallel electrodes include: handling and feeding two electrodes instead of one; two electrodes are somewhat more difficult to position properly; electrode alignment can affect root penetration; and smaller electrodes tend to wear out the electrical contacts faster because they are fed at much higher speeds. Another possible detriment to parallel electrodes is an increase in diffusible hydrogen compared to welding with a single electrode due to the difference in the surface areas of an otherwise equal volume of single and parallel electrodes.

SAW electrodes used in bridge construction are typically coated with copper to improve the electrical contact between the welding equipment and the electrode. This coating also helps to protect the electrodes against corrosion. The thin coating of copper on SAW electrodes has no adverse effect on weld properties. Solid SAW electrodes are also coated with a lubricant to assist in feeding the electrode. Lubricants generally have no adverse effect on weld properties, but in the case of small parallel electrodes that have much more surface area to weight of electrode, the greater amount of lubricant may be a source of hydrogen.

C-6.7.2 WPS Limitations. When welding quenched and tempered steels, there is a significant potential for reduced strength and toughness in the HAZ if the welding heat input used in conjunction with the preheat or interpass temperature is too high. The steel manufacturer's recommendations for maximum welding heat input, at a given preheat or interpass temperature and thickness, should not be exceeded.

C-6.7.3 Surface Preparation. All foreign materials that would interfere with fusion or contaminate the weld and HAZ with hydrogen and other deleterious material must be removed prior to welding (see C-5.2.1).

C-6.7.6 Depth-to-Width Ratio. The weld nugget or bead shape is an important factor affecting weld cracking. Solidification of molten weld metal due to the quenching effect of the base metal starts along the sides of the weld metal and progresses inward until completed. The last liquid metal to solidify lies in a plane through the centerline of the weld. If the weld depth is greater than the width of the face, the weld surface may solidify prior to the center solidification. When this occurs, the shrinkage forces acting on the still hot, semi-liquid center or core of the weld may cause a centerline crack to develop. This crack may extend throughout the longitudinal length of the weld and may or may not be visible at the weld surface. This condition may also be obtained when fillet welds are made simultaneously on both sides of a joint with the arcs directly opposite each other.

C-6.7.7 Tack Welds. Large tack welds may interfere with penetration at the root and may produce irregular weld surface contours. When penetration or weld appearance is adversely affected by the presence of tack welds, they must be removed or reduced in size so that they do not interfere with the welding. When steel backing is less than 8 mm [5/16 in] thick, the energy necessary to remelt tack welds may also be sufficient to melt through the backing. When thin backing is used, the tack welds must be removed or made continuous. These provisions do not supersede or modify the provisions of 5.3.7.

Tack welds made without preheat should be completely remelted to ensure soundness of the final weld and the HAZ. See C-5.3.7 for a discussion of tack welds and their influence on fatigue life.

C-6.8 Electrodes and Fluxes for SAW

C-6.8.1 Electrodes and Fluxes. The chemical composition limits of the electrodes, or of the deposited filler metal in tests, and the required mechanical properties of the test welds are listed in AWS Specifications A5.17/A5.17M and A5.23/A5.23M. Carbon and alloy steel electrodes and fluxes are separated in these specifications in a manner similar to that used in SMAW. The classification system for SAW electrodes and fluxes is detailed in the annexes of the AWS A5.17/A5.17M and AWS A5.23/A5.23M filler metal specifications. Most SAW electrodes are furnished as solid bare electrodes with a light coating of copper to improve electrical contact and resist corrosion. Alloy steel electrodes may be furnished as solid bare electrodes or as composite, cored, or tubular electrodes. The chemical composition of solid electrodes is determined by chemical analysis of the electrode. The chemical composition of composite electrodes is not measured directly. Instead, a weld is made under conditions that minimize the influence of base metal, and the chemical composition of the deposited weld metal is used for classification purposes.

Submerged Arc Welding Fluxes—General. Good, high quality SAW welds free from hydrogen contamination are dependent on good, clean, dry flux and electrodes. Any condition that leads to loss or segregation of flux components, or that contaminates the flux with ingredients that interfere with welding or introduce hydrogen into the weld and HAZ, may lead to welding problems.

Fluxes are made by four basic processes and are classified as neutral, active or alloy fluxes, based on their performance during welding.

Fused Fluxes. Fused fluxes are made by blending deoxidizing and alloying ingredients, as necessary, and then heating the mixture in a furnace until it is completely melted. A glass-like fused product is formed as the liquid is cooled to ambient temperature. The fused flux is later ground to the sizes required for welding. Fused fluxes are nonhygroscopic, meaning they will not absorb water. Fused fluxes can be contaminated by moisture or other products that adhere to the outside of particles. Fused fluxes are not subject to chemical segregation during reuse because the complete composition is in each particle and cannot be separated. Fused fluxes may have less than desired amounts of deoxidizer and ferro-alloy ingredients because of losses that occur from the high temperatures during the manufacturing process. Fused flux performance can be impeded by loss of fines during recycling.

Bonded Fluxes. Bonded fluxes are made by combining all required chemical ingredients with a binder and baking the product at low temperature to form hard granules that are then broken up and screened for size. Bonded fluxes contain chemically bonded moisture and can absorb moisture as well. There is no problem with deoxidizer content or alloying elements that can be added as ferro-alloys or as elemental metals because the product is baked at low temperature. Bonded fluxes may segregate during use and reuse and gases may be produced in the molten slag during welding. Bonded fluxes tend to break down during recycling and increase the percentage of fines.

Agglomerated Fluxes. Agglomerated fluxes are similar to bonded fluxes in their method of manufacture, except that the binder is a ceramic material that requires baking at higher temperatures. This may limit deoxidizer or ferro-alloy content due to high temperature losses. Agglomerated fluxes are generally considered nonhygroscopic but are not as completely moisture resistant and moisture free as fused fluxes.

Mechanically Mixed Fluxes. A fourth group of fluxes is called mechanically mixed. It can be a mixture of any flux types, in any desired proportion. Mechanically mixed fluxes are subject to segregation and will have the attributes of their components.

Good quality welds made with SAW require fluxes that have the proper chemical composition, particle size distribution, and a very low moisture content. Fused fluxes with the required chemical composition generally give the best low-hydrogen welding performance and are not subjected to chemical segregation in use. Another factor is the selection of an active, neutral, or alloy flux. A definition of active, alloy, and neutral fluxes is given in Clause 3, Terms and Definitions. A more complete description is provided in the annexes of the AWS A5.17/A5.17M and AWS A5.23/A5.23M filler metal specifications.

Neutral fluxes are those in which changes in welding procedure variables, primarily the voltage that determines arc length, have little effect on the chemical composition of the deposited filler metal, specifically the manganese and silicon content. For both active and alloy fluxes, the resultant weld metal chemical composition will vary according to arc voltage.

Active fluxes are often desirable for use in making single pass fillet welds as these fluxes produce welds that are more resistant to porosity and cracking than welds made with neutral fluxes. These fluxes have slight additions of manganese and silicon, or both, to help offset the effects of welding through mill scale and light coatings of rust. Active fluxes can introduce manganese that can offset the weld cracking tendencies that increase with increasing sulfur levels in the steel. The higher silicon encourages better wetting at the toe radius and enhanced fatigue resistance in some cases. However, active flux/electrode combinations are often limited in multiple pass applications due to the increases of manganese and silicon. Caution must be exercised when welding with active fluxes. A significant change in arc voltage will change the weld metal chemical composition and the mechanical properties of the weld.

Unused flux may be recovered and reused. Typically called "recovery," if this practice is ongoing without a program of replenishment, the flux properties may change due to mechanical breakdown of the particles (see C-6.8.3). The filler metal classification tests require that weld metal properties be determined from a multipass, groove welded test plate. However active fluxes are primarily used for single pass fillet welding. This code restricts the use of active flux to one or two pass applications, unless approved by the Engineer (see 7.5.2). Manganese and silicon obtained from the flux during welding may combine with the same elements in the electrode to produce weld metal with unacceptable properties. This is not a problem in single- or two-pass welds but the chemical composition may build to unacceptable levels in larger multipass welds. This problem can be avoided, to some degree, by welding with electrodes that have low levels of manganese and silicon. If proper procedures are followed, however, active fluxes can and have been used successfully. Key to successful usage is the control of arc voltage during production welding and selection of the proper electrode to be used with the flux. The manufacturers' guidelines on maximum voltage levels should be followed.

Alloy fluxes contain ingredients intended to improve the strength or corrosion resistance of the weld metal, or both. Alloy fluxes, properly used with carbon steel electrodes, provide a low-cost method of producing corrosion resistant weld metal for joining weathering steels. Alloy fluxes generally do not produce unacceptable build-up in the level of chemical elements in multipass welds. Still, proper control of arc voltage is required.

C-6.8.2 Condition of Flux. When flux is exposed to the open atmosphere in an open bag or hopper, the flux may absorb moisture. When welding operations are not resumed within 24 hours, flux that has been open to the atmosphere is required to be replaced. During the week of a single shift operation, the flux in open hoppers could be left exposed.

However, if the welding equipment is not used for one day, such as is the case over a standard weekend, the flux must be replaced before welding operations resume.

Closed systems have engineered enclosures that effectively restrict the exchange of air within and without the system. Closed flux delivery systems, such as pressurized tanks and some vacuum recovery systems, provide additional protection from the atmosphere. Flux in these systems is permitted to remain when welding is suspended for up to 96 hours. This permits the Contractor to leave flux in such systems over three day weekends, or other three day periods where production may be interrupted for other reasons.

The 24-hour and 96-hour rules were established to prevent continuation of welding with existing flux after major shutdowns.

If flux comes in direct contact with water, it is to be discarded. It may not be dried and subsequently used.

C-6.8.3 Flux Reclamation. Contractors are allowed to recover and reuse flux that has not been melted or contaminated by dirt, moisture, or any other material that will adversely affect welding properties. Recovering flux immediately after welding helps to keep it clean and dry, so flux left more than one hour must be dried before reuse.

When fluxes are reused, they tend to lose their fines and may become chemically segregated. Some flux is consumed and a certain amount is lost. The Contractor is required to have a reliable method for adding additional new, unused flux in sufficient amounts to make up for all losses and to ensure that the flux used in welding is unvarying compared to the flux approved for welding based on qualification tests. To conform to this requirement, new flux in amounts of 25% to 50%, by volume, is commonly added to reclaimed flux before reuse.

Screens and magnets may be used to remove mill scale and other metallic debris that may clog the flux supply system or affect the weld performance through arcing or chemical additions. However, some alloy fluxes are magnetic and may become magnetized in this operation, affecting the arc. For such alloy fluxes, the magnet should not be used.

C-6.9 Procedures for Submerged Arc Welding with a Single Electrode

C-6.9.1 Position. Due to the relatively large weld pool and flux burden with submerged arc welding, it takes a relatively long time to solidify. SAW can be used effectively in the horizontal position, though extra care is necessary to ensure a good profile and fusion to the nonhorizontal face. The use of DC– (DCEN) minimizes distortion and may improve weld profile.

C-6.9.2 WPS Limits. Welding parameters must be adjusted to produce sound welds. These restrictions on current represent good practice but the maximum current must not exceed the limits qualified by WPS testing. Current, voltage, travel speed, and placement of individual weld passes in weld preparations of various contours determine the final weld bead volume, shape and depth. Restrictions on current alone will not ensure soundness, mechanical properties, or freedom from cracking.

C-6.9.3 Maximum Layer Thickness and Width. These provisions effectively limit welding heat input and promote beneficial reheating by subsequent weld passes. Multipass welds made with many passes and layers typically have better mechanical properties, particularly toughness, than welds made with fewer passes. However, the use of many weld passes may increase shrinkage stress and distortion. Split-layer welding techniques ensure that there is complete fusion throughout the complete cross section of the weld. In subsequent passes, the welding heat input can be increased (within the limits of the WPS). Split layer techniques are not mandatory until the width of the layer exceeds 16 mm [5/8 in], but may be used for root openings or layer widths less than these limits.

C-6.10 Procedures for SAW with Parallel and Multiple Electrodes

Welding with two parallel electrodes receiving power from the same source is not materially different from welding with a single electrode, except that the two parallel electrodes are generally smaller and fed at higher wire feed speeds, and the electrodes may be oriented in a tandem configuration, parallel to the weld axis or displaced laterally by rotating the welding head. When the welding head and contact tube is rotated 90° so the parallel electrodes are displaced perpendicular to the weld axis, the weld pool is widened and fusion at both sides of the weld is improved. Welding in this manner decreases penetration, which is sometimes desirable to reduce the amount of dilution from the base metal.

C-6.10.1 Weld Layer Width. Weld layer width limits help ensure proper fusion of weld passes.

C-6.10.2 Weld Layer Thickness. The thickness of weld layers is not controlled with direct size limits but rather by whether the fabricator can achieve code quality requirements and good workmanship.

C-6.10.3 GMAW Root Pass. GMAW is very effective in getting into narrow root openings, and because of lower heat inputs, it can bridge root gaps that SAW would burn through. Further, GMAW produces clean welds that do not have a layer of welding slag that has to be removed before a following SAW pass can be applied. Though SAW procedures often use multiple electrodes feeding a common weld pool (see Table 7.6), a leading GMAW pass does not feed the same weld pool and can be made in advance of the trailing SAW. The GMAW can solidify and partially cool without interfering with the final SAW. A typical spacing is 150 mm or 200 mm [6 in or 8 in] between arcs.

The leading GMAW weld may be considered a continuous tack weld that can be made without preheat, provided it is completely remelted by the trailing SAW. In some cases, the GMAW can provide the minimum preheat required by Table 6.3 for the SAW. When this technique was initially developed, the benefits of slow cooling to permit the diffusion of hydrogen were not widely known. The only criteria were minimum preheat and interpass temperature. In routine applications, this approach has produced acceptable results, mostly in T- and corner joints. In heavy sections, additional preheat may be required to prevent weld or HAZ cracking. All WPSs, including this rather unique one, require qualification and approval of the Engineer. Welding by GMAW, SAW, or a combination of the two processes must conform to all code requirements for these processes.

C-6.10.4 Preheat and Interpass Temperatures. If the welding heat input from a single pass SAW weld is sufficient to produce a "soft" HAZ, satisfying the hardness limits specified, the preheat and interpass temperature may be reduced below that specified in Table 6.3. A Vickers Diamond Pyramid Hardness Number of 225 represents a Rockwell C Hardness of less than R_c 20, the softest value on the Rockwell C scale. A Vickers DPH Number of 280 is approximately equal to Rockwell C27. The Rockwell indentor is too large to make accurate measurements of the hardness of small areas of the HAZ, so Vickers or Knoop microhardness measurements are preferred. Portable Rockwell Hardness Testers may be used to provide approximate results as specified in 5.3.7.4.

When the welding heat alone is sufficient to produce low hardness HAZs as specified, the risk of hydrogen-assisted cracking is low. This provision and all others that depend on welding heat input to produce acceptable HAZ properties assume that the welding heat is constant and uninterrupted. This can be achieved in SAW by starting on a joint extension so that the welding heat, by conduction, helps to preheat the base metal. If the weld is started on main material, with no preheat prior to arc start, the HAZ may be unacceptably hard regardless of the heat input.

C-6.10.4.1 HAZ Hardness Determination. A smooth surface is necessary for testing, but material removal should not be so deep as to reduce the section's capacity or so aggressive that heat from surface preparation may affect the test area hardness.

C-6.10.4.2 Fillet Welds. Welding heat input is generally proportional to the square of the weld size. When fillet welds are 10 mm [3/8 in] or less in size, the welding heat input (without the added preheat) may not be sufficient to produce a "soft" (more ductile) HAZ (see C-6.10.4).

Part D
Gas Metal Arc Welding (GMAW) and Flux Cored Arc Welding (FCAW)

C-6.11 GMAW/FCAW Electrodes

GMAW and FCAW electrodes are separated in the filler metal specifications based on alloy content. In general, filler metals with minimum specified tensile strengths greater than 490 MPa [70 ksi] are listed in the alloy filler metal specifications. Lower strength filler metals are listed in both carbon steel and alloy filler metal specifications.

The actual electrodes permitted are listed in Table 6.1.

C-6.12 Shielding Gas

It is essential that the gas or gas mixture used to shield GMAW and FCAW is dry. Even a slight amount of moisture in the shielding gas can lead to porosity or hydrogen contamination of the weld. To ensure that the shielding gas is dry, a very low dew point is specified. If there is insufficient moisture in the gas to condense at any temperature above that required in AWS A5.32/A5.32M, the gas is dry enough to be used in welding. Some FCAW electrodes are self shielded and do not need an external shielding gas of any kind.

C-6.13 Procedures for GMAW and FCAW with a Single Electrode

C-6.13.1 General

C-6.13.1.1 Electrode Condition. Electrodes must be dry and clean when used. Electrode manufacturers package electrodes to allow storage of indefinite duration, without damage from moisture or other contaminants. Once removed from the plastic envelope, the electrodes may pick up moisture and become contaminated by foreign material and rust.

All electrodes should be protected from dirt and moisture; however, the use of rod or wire ovens is not generally required for non FCM work. Electrodes that become rusted are unsuitable for welding, and if water (rain or snow) falls on the reels, it may not be possible to effectively dry them to prevent rust or adsorption.

C-6.13.1.2 Maximum Electrode Diameter. These are the maximum size electrodes that can be handled effectively in the positions indicated as established by good welding practice.

C-6.13.1.3 Maximum Single Pass Fillet Weld Size. Sound welds with acceptable appearance and good mechanical properties can be made up to the sizes specified. When larger welds are attempted in one pass the welds are often less desirable in appearance and mechanical properties. It takes considerable skill to make overhead welds of the maximum size in a single pass. A vertical fillet weld larger than 12 mm [1/2 in] is relatively easy to produce in one pass, but would have less toughness because of its size and slow cooling rate. These maximum sizes represent the limits of good practice.

C-6.13.1.4 Maximum Layer Thickness and Width—GMAW. These provisions effectively limit welding heat input and promote beneficial reheating by subsequent weld passes. Multipass welds made with many passes and layers typically have better mechanical properties, particularly toughness, than welds made with fewer passes. However, the use of many weld passes may increase shrinkage stress and distortion.

Split layer welding techniques are required to ensure that there is complete fusion throughout the cross section of the weld. In subsequent passes the welding heat input can be increased (within the limits of the WPS). Split layer techniques are not mandatory until the width of the layer exceeds 16 mm [5/8 in] but may be used for root openings or layer widths less than these limits. Changes in current, voltage, and travel speed must be supported by WPSs that have been qualified by test.

C-6.13.1.5 Maximum Layer Thickness and Width—FCAW. This provision is the same as that for GMAW in C-6.13.1.4, except that when welding in the vertical position, required to be performed vertical-up, a split layer technique is not required until the layer width exceeds 25 mm [1 in]. The higher heat input, good shielding, and light slag cover of FCAW permits a 25 mm [1 in] maximum weave width.

C-6.13.1.6 WPS. Welding parameters must be adjusted to produce sound welds. The procedure must be controlled so that there is no overlap or unacceptable undercutting and performed in a manner that produces good fusion and resists cracking. Slightly convex weld bead surfaces are preferred to concave weld surfaces to avoid weld cracking, particularly in the root passes of highly restrained joints.

C-6.13.1.7 Vertical Progression. The progression of all vertical weld passes is required to be vertical-up to ensure that there is sound fusion and that the welding heat input is sufficient to prevent cracking. Welding may be done in the vertical down position if a procedure qualification test is successfully completed and approved by the Engineer.

C-6.13.2 CJP Backgouging. This provision applies to all welding processes approved for use under this code and is designed to ensure a high degree of weld soundness in CJP groove welds. Weld discontinuities such as slag and porosity at the unprotected root must be removed until only sound weld metal remains, and gouged areas must be ground to bright metal per 5.2.6, to remove any potential carbon or copper deposits that may remain after gouging.

C-6.13.3 Maximum Wind Velocity. Wind velocities in excess of 8 km/hr [5 mph] per hour may disrupt gas shielding sufficiently to cause weld defects or adversely affect mechanical properties, particularly toughness.

C-6.13.4 GMAW Short-Circuiting Process. This mode of transfer with the GMAW process, designated GMAW-S, may result in welds with fusion defects called cold laps, particularly when applied to materials of thicknesses typical of main bridge members. The welds may also have excessive weld splatter. However, the process-mode is capable of being used in all positions, something that is not possible with GMAW-spray, for example. Caution should be exhibited when GMAW-S is used for structural applications. Any GMAW WPS with an electrode diameter of 1.2 mm [0.045 in] or less and a weld voltage of 20 V or less must be visually monitored to ensure no short circuiting transfer occurs. See Annex C for nonmandatory guidelines to determine the type of transfer.

C-6.17.5 See Annex O.

C-6.18.2 See Annex O.

C-6.18.3 See Annex O.

C-6.19.2 Consumable Guides. See Annex O.

C-6.20 Condition of Flux. See Annex O.

C-6.21 Consumable Guide Electrical Insulators. See Annex O.

C-6.22.2 See Annex O.

C-6.22.3 See Annex O.

C-6.22.4 See Annex O.

C-6.22.5 See Annex O.

C-6.22.6 See Annex O.

C-6.22.8 See Annex O.

C-6.22.8.1 Voltage. See Annex O.

C-6.22.8.2 Travel Speed. See Annex O.

C-6.22.8.3 See Annex O.

C-6.22.9 See Annex O.

C-6.22.10 See Annex O.

C-6.22.11 See Annex O.

C-6.22.15 See Annex O.

Part G
Plug and Slot Welds

C-6.23 Plug Welds

The technique provided to make plug welds has been used for many years. SAW is not listed as an approved process because the heavy slag cover and buried arc makes continuous welding in this manner unacceptable. All processes approved for welding in this manner are open arc processes where the welder is able to visually verify that fusion is being achieved. As slag depths increase, it becomes more difficult to see the arc and the likelihood of fusion defects increases. Also, slag may flow under the arc, and make fusion with the base metal or previously deposited weld metal impossible.

Plug and slot welds must not be used on primary members subjected to tensile loads. Historically, plug and slot welds have had a relatively high incidence of fusion defects and have been the site of fatigue crack initiation. Further, plug and slot welds have limited stress range capability, even when properly made. If these welds are specified, the quality of such welds must be carefully controlled (see C-4.8 and C-6.25).

C-6.23.1 Flat Position. This method of welding is intended to be an orderly progression of the arc around the perimeter of the hole in the root, then spiraling to fill the rest of the root layer. Welding must be continuous to keep the slag molten at the point of welding, progressively floating it to the top. This is extremely difficult to do with welding processes that have heavy slag. Subclause 6.25 requires better controls over welding using this technique to reduce the number of fusion defects and the amount of slag entrapped in the weld.

C-6.23.2 Vertical Position. When welding in the vertical position in a hole or slot, the weld must be cleaned of slag after the completion of each weld pass. Lack of fusion and slag entrapment is less of a problem when welding in the vertical position because the slag runs down the face of the weld layer. The most difficult area to achieve complete fusion is in the root layer at the top of the hole circumference. Welding is generally done by weave techniques, starting in the bottom of the hole and working without interruption to the top.

C-6.23.3 Overhead Position. When welding in the overhead position, it is difficult to use enough welding heat to keep the slag molten so that another layer can be welded without stopping to remove the slag. Therefore, welding is done with lower currents and welding is stopped to remove all slag before starting another weld layer. If too much heat is used, the slag and weld metal will drip.

C-6.24 Slot Welds

Slot welds are not the same as fillet welds in the slot. Slot welds are plug welds using an elongated hole. Fillet welding in a slot is simply another application or arrangement of fillet welds. When the slot is sufficiently elongated, it is impossible to keep the slag hot long enough to permit continuous welding. The weld must be allowed to cool and the slag must be removed between weld layers.

C-6.25 Plug and Slot Welds

Welding by the continuous plug welding technique becomes increasingly more difficult as slag depth accumulates. As slag cover depths decrease, it becomes much less difficult to make sound welds. Therefore, GMAW may be best suited for welding in this manner. When slag interferes with fusion, there are many clear signs that the welder can identify. When these signs are present, welding should be stopped and the slag removed before continuing.

Part H
Control of Production Welding Variables

C-6.27 Control of Variables

Each weld must be made in conformance with an applicable WPS prepared by the Contractor. WPSs, except those addressed in 1.3.7 or 7.11, are written based on acceptable procedure qualification tests. All welding procedure variables must be controlled in the work. Welding variables affect weld bead size and shape, weld layer depth, and conditions that determine ease of slag removal and the tendency to produce undercut. The welder or welding operator must adjust the equipment to maintain the specified variables in order to produce sound welds of the required size and quality. All adjustments of the equipment and variables must be within limits established by the code.

The controls listed in Part H are intended to ensure that production welding is properly regulated and that the welding variables are based on the results of successful PQRs.

C-6.28 Calibration of Equipment

C-6.28.1 Verification. All production welding should be performed using variables consistent with the WPS. This requires accurate meters and gages on the welding equipment for both qualification and production. Meters and gages should be checked regularly for accuracy and repaired or replaced as necessary.

C-6.29 Current Control

C-6.29.1 Wire Feed Speed. Current is roughly proportional to wire feed speed. Modern semiautomatic and automatic welding units typically monitor, control, and display wire (electrode) feed speed, rather than current. In welding units that utilize constant potential (voltage) power sources, the electrode is fed into the weld pool at a constant rate. As the wire feed speed is increased, the current also increases. The relationship between current and wire feed speed may not be linear throughout the full current range. As long as the current/wire feed speed relationship is established and documented, the WPS can be controlled by wire feed speed instead of, or in addition to, current.

C-6.29.2 Correlation Data. The Inspector is required to have access to the current/wire feed speed correlation data. Both the PQR testing and production welding may then be controlled by use of wire feed speed but the heat input is required to be calculated using current (not wire feed speed).

C-Table 6.3 Minimum Preheat and Interpass Temperature. This table lists the minimum preheat and interpass temperatures that are acceptable for routine welding, with two exceptions. When high welding heat input procedures are used, it is possible to provide less preheat and still avoid cracking. The first exception is for parallel electrode and multiple electrode SAW as provided in 6.10.4. The second exception permits reduced preheat temperatures if calculated using Annex F, as provided in 6.2.1.2, then proven on the basis of tests approved by the Engineer and conducted following the provisions of 7.12.4.

Higher preheat temperatures and greater lateral and through thickness heating of the base metal should be considered when welding thick or highly restrained joints. All repair welding that requires groove preparation should be considered highly restrained because the joint is already welded and locked into place, or is solid base metal alone, and is restrained from shrinkage in all directions.

C-7. Qualification

Introduction

C-7.0 Scope

Two types of qualification tests are described in this clause: *Welding Procedure Specification (WPS) Qualification Testing* as contained in Part A, and *Qualification Testing of Welding Personnel* as contained in Part B.

Qualification of WPSs is required by this code to demonstrate that welds of the required soundness and mechanical properties can be achieved.

The strength, ductility, and toughness of the deposited weld metal depend on the (a) weld metal chemical composition, (b) cooling rates experienced by the weld metal, and (c) subsequent heating (if any) of the deposit. Similarly, the properties of the HAZ are influenced by the same factors except that the chemical composition involved is that of the base metal that is not changed by welding.

The weld metal chemical composition is dependent on the chemical composition of the filler metal and the base metal composition. Most of the composition of the weld metal is provided by the electrode and, where applicable, flux. A portion comes from the base metal, including fused backing. Welding variables may affect the weld chemical composition. Higher amperages are associated with deeper penetration, which, in turn, introduces more of the base metal into the weld pool. Alternately, low amperage WPSs will have welds that are more dependent upon the filler metal composition.

The cooling rate associated with a weld deposit and the HAZ are dependent on many factors. Slow cooling rates are encouraged with higher levels of preheat and interpass temperature, higher heat input levels, and thinner plate thicknesses. Conversely, high cooling rates are associated with low preheat and interpass temperatures, thicker plates, and low heat input levels.

High cooling rates generally result in weld metal and HAZs that are higher in strength, lower in ductility, and lower in toughness. Slow cooling rates are associated with lower strength welds and HAZs, greater ductility, but also lower toughness. The optimum balance of strength, ductility, and toughness is achieved when cooling rates are properly positioned between these two extremes.

The toughness of a weld deposit is particularly sensitive to welding parameters, and cooling rates that are either too rapid or too slow may negatively affect toughness. Rapid cooling rates result in acicular grain structures that are typically lower in toughness. Slow cooling rates result in very large grains that are also low in toughness. Optimum cooling rates result in an equiaxed grain structure, with optimal toughness.

High cooling rates minimize the time for hydrogen diffusion while slower rates maximize the opportunity for hydrogen to migrate out of the weld and HAZ.

Balance is therefore required in order to maintain an appropriate level of strength, ductility, toughness, and diffusion of hydrogen.

Multiple pass welds subject previous weld passes to additional thermal cycles, reheating portions of the previously deposited weld, generally resulting in improved notch toughness. This also results in a reheating of the HAZ and changes in that region as well. Single-pass welds are not subject to this generally beneficial reheating of the weld.

The WPS qualification tests imposed by this code are not designed to measure the resistance of a weld metal or base metal to hydrogen-induced cracking. The low restraint associated with these test plates makes it unlikely that this type of cracking would be detected except under the most extreme conditions.

Weld soundness depends on the proper combination of welding variables (amperage, voltage, travel speed, etc.) in combination with the joint of the proper geometry (root angle, root opening, etc.). When standard welding joints as illustrated in Figures 4.4 and 4.5 are used, no specific tests of the joint detail are required as these joint details have a long history of satisfactory performance. When details differ from these joints, specific tests are required to determine the suitability of the combination of welding variables to the particular joint detail.

There is no practical method to measure fillet weld properties, particularly for small, single-pass welds. While acknowledging that there may be significant differences between the properties of these welds and groove welds, the code nevertheless requires that fillet weld WPSs be qualified by testing weld metal deposited in groove welds and by performing soundness tests. Fillet welds are typically loaded in shear and therefore not loaded significantly, and the required toughness of such welds is unknown. As a result, there is no requirement to quantify by test actual fillet weld properties.

The code requires simple tests that can verify the skill level of the welding personnel who will be performing the welding. Even with a good WPS, poor technique or setup skills may create discontinuities that may initiate fatigue cracking. Welding personnel qualification testing is as described in Part B.

Part A
Welding Procedure Specification (WPS) Qualification

C-7.1 Approval

Procedure qualification records (PQRs) are records of the actual variables used to qualify a welding procedure specification (WPS) by test. On WPSs, the code permits some variation of essential variables from the values tested in the PQR. Frequently a preliminary WPS is used as the basis for a PQR test, which then records the measured values of variables as the foundation for the final production WPS.

See C-7.2.3 for approval practices among bridge owners.

C-7.1.1 Purpose of WPS Qualification Tests. These provide assurance that the production welding to be performed will provide the strength, ductility, and toughness required by the design. AWS D1.1, *Structural Welding Code—Steel*, allows WPSs to be prequalified, exempt from WPS qualification testing, when in conformance to specific requirements. Because toughness is important for bridge performance, and because weld toughness is dependent on not only the filler metal used, but also the combination of welding parameters employed, WPS qualification testing is generally required by this code.

Tests to classify welding consumables, including electrodes and electrodes used in combination with fluxes or shielding gas, are described in the AWS A5.XX filler metal specification series. These test WPSs are not intended to duplicate all production welding conditions or WPSs. The WPSs followed by the manufacturer or testing firm for filler metal classification testing are very specific and uniform, done under the specified test conditions, so that the results of common tests can be compared.

There may be a substantial difference between the mechanical properties of welds made by welding consumable classification tests and the strength, ductility, and toughness measured when test specimens are made from actual production welds.

As an example, applicable specifically to SAW, electrodes and fluxes are produced under the provisions of AWS A5.17/A5.17M or A5.23/A5.23M, for carbon steel electrodes and low-alloy steel electrodes, respectively. Carbon steel electrodes and fluxes are tested by welding at 28 V. Alloy steel electrodes and fluxes are tested by welding at 26 V to 32 V, depending on the electrode diameter. Typically, fifteen weld passes are deposited in seven weld layers on the 25 mm [1 in] test plate. However, production welding may routinely use higher voltages, affecting the amount of flux melted. This, in turn, can affect the weld chemical composition, especially when active fluxes and alloy fluxes are used (see C-6.8 for a description of SAW electrodes and fluxes). Mechanical properties such as strength, ductility, and toughness may be affected.

One method for ensuring that production weld metal properties created by a particular WPS meet all the code requirements would be to test each individual WPS, allowing no variation in welding parameters. In addition to requiring requalification for all changes in welding consumables and WPS variables, retesting would also be required for significant changes in base metal thicknesses and for each grade of steel to be welded. However, it would be impractical and unwarranted to test every set of conditions that would be used in production. Tests that allow a broader range of WPS variables are used to keep the required number of WPS qualification tests to a minimum.

Weld metal produced by welding in conformance with the provisions of WPSs proposed by the Contractor should produce mechanical properties that conform to the requirements of Table 7.3. Because filler metal classification tests may be conducted under different welding conditions, the weld metal produced by D1.5 qualification tests are not required to satisfy the same requirements as the applicable AWS filler metal specification.

Consistent weld soundness and mechanical properties requires adherence in production to a good WPS. The testing procedures described in the code evaluate the suitability of essential variables based on differences in calculated heat input. In addition to specifying qualification testing procedures, the code also specifies methods for the control of welding variables in production.

Little assurance of actual weld performance would be offered if welding parameters were allowed to vary significantly from the values tested. The adjustment of voltage, current, and travel speed allowed in Table 7.4 could allow the welding heat input to vary such that maximum welding heat input could be twice the minimum welding heat input. That may not be acceptable for bridge construction, where toughness is critical to safety, unless tests are used to verify that the specified minimum toughness will be produced. The WPS qualification tests described in this subclause, together with the procedures for control of welding variables described in Clause 6, Part H, provide confidence that production welds will achieve the mechanical properties required by the code or contract documents.

The mechanical properties described in Table 7.3 for qualification, pretest, or verification testing are suitable for bridge construction. The Engineer may accept other values using engineering judgment. The notes to Table 7.3 provide guidance regarding the justification and approval of alternate test results.

In addition to providing for the qualification and control of WPSs based on the maximum welding heat input, provisions are also made for maximum/minimum “envelope” heat input testing and control. This qualification option was developed to provide assurance of good mechanical properties, while using a minimal number of qualification tests, to evaluate the extremes in welding heat input.

C-7.2 Qualification Responsibility

The Contractor is responsible for all qualification and verification testing, demonstrating that the Contractor can produce the results described by the code. The Contractor cannot delegate responsibility for qualification testing to a third party. When a choice between qualification methods is provided, the Contractor may select the option that best suits the situation.

C-7.2.2 Contractor. It is the Contractor’s responsibility to perform the WPS qualification tests required by the code. Written WPSs are then produced for use in production welding.

C-7.2.3 Previous Qualification. The acceptability of qualification using other standards is at the Engineer’s discretion, to be exercised based on the standards used, the structure, and service conditions.

This provision is intended to encourage reciprocity between Owners (States), avoiding unnecessary cost and potential time schedule delays associated with duplication of testing.

In practice, approval policies among bridge owners vary. When AASHTO first joined with AWS to produce the *Bridge Welding Code*, broad reciprocity of welding procedures was a leading motivation. Many owners follow the practice of accepting welding procedures approved by other owners who verified the PQR.

C-7.2.4 Excess Testing. Tests in excess of those required by the code are considered extra work subject to payment by the Owner. When extra tests are necessary, the Owner may include extra testing requirements in the contract by listing the required tests in the contract documents prior to bidding. When this is done, the Contractor is informed of the extra testing in advance and can include the cost in the bid. Additional testing is not routinely justified because the code testing requirements are generally adequate for the bridge structures covered by the code.

The Engineer may order appropriate requalification tests whenever WPSs produce unacceptable results.

C-7.2.5 Records. PQRs and WPSs should be available for review by the Inspector, Engineer, or Owner.

C-7.3 Duration

Previous editions of the code had time limits on PQRs. These were removed because bridge welding experience and associated testing under this code demonstrated that repeated tests of the same welding parameters did not offer additional useful information about the properties of the welds accomplished with the procedure nor an effective reflection of the fabricator's welding practices.

C-7.4 Base Metal

C-7.4.1 Base-Metal Qualification Requirements. The chemical composition of the steel used as test plates and steel backing can affect test results. Chemical elements obtained by pickup, also called dilution, from the base metal can affect hardness, strength, ductility, and toughness. However, the restriction of base metals to the grades of AASHTO M270 or ASTM A709 listed in 1.2.2 means that there will be no unexpected interactions between base metal and weld metal. Qualification to this code primarily tests the weld metal. Steel for qualification test plates is selected to approximately "match" the weld metal; therefore, there is no separate testing for undermatched or hybrid joints. The relationship between the qualification test and the base metal qualified for use in production is addressed in 7.19.3, which establishes that the mechanical testing results must be as appropriate for the base metal to be used in production. Matching filler metal WPSs are also governed by Table 6.1.

Table 7.1 lists test plate materials that may be selected to qualify a WPS for a given combination of filler metal and base metal. The test plate material is not required to be the same material that will be used in production, as long as the qualification test meets the requirements of Table 7.1. For example, to qualify a WPS using Gr. 36 plate and E61T1 electrodes, it is permissible to use Gr. 50 base metal for the test plate. For a WPS using Gr. 50W plate and E8XT1 electrodes, it is also permissible to use Gr. 50 base metal for the test plate, but per 7.19.3.1 and Table 7.3, the required tensile strength would be 70 ksi. 7.19.3.2 addresses how to use Table 7.3 when qualifying undermatched WPSs.

The standard tests required by the code for WPS qualification testing do not evaluate base metal, or HAZ CVN test values; therefore, the base metal for WPS qualification testing is not required to have minimum specified CVN test values. Having such CVN test values is desirable, but not required. The lack of specified CVN test values may negatively affect some test results, particularly if HAZ CVN testing has been specified in contract documents.

The ASTM equivalents to M270 (A709) grades listed in Table 7.2 are identical to the M270 (A709) grades except for required CVN testing. Since CVN testing of base metal is not required for test plates, these steels are acceptable for that use.

C-7.4.2 Use of Unlisted Base Metals. The testing required in 7.12.4 provides information about mechanical properties, weldability, and effect of heat input and cooling rates on the mechanical properties of the steel, weld, and HAZ. See C-7.15.1 for discussion of testing for undermatched or hybrid joints.

The ASTM equivalents to M270 (A709) grades listed below are identical to the M270 (A709) grades except for mandatory CVN testing. In the event that the use of these ASTM steels is permitted or required in production (for example, where plate thicker than 200 mm [4 in] is required), the Engineer should accept WPSs qualified for the equivalent M270 (A709) steels without further testing.

M 270M/M 270 (A709/A709M) Grade	ASTM equivalent
250 [36]	A36/A36M
345 [50]	A572/A572M Gr. 345 [50]
345S [50S]	A992/A992M
345W [50W]	A588/A588M Gr. A or B

C-7.4.2.1 The contract documents may also require CVN testing of the HAZ. CVN testing of the HAZ is rarely done for WPS qualification for bridge applications. Therefore, when the contract documents require HAZ toughness testing, detailed instructions should be provided for the testing procedure.

CVN testing of the HAZ can determine if the properties of the base metal have been affected by the heat generated from welding. Quenched and tempered steels achieve their high strength and good toughness, in large part, to fine grain produced by the heat treatment. High welding heat inputs that subject the HAZ to high temperatures for long periods may cause the HAZ grains near the fusion line to grow or coarsen. Grain coarsening generally reduces toughness. The most serious degradation in toughness occurs within 2 mm [1/16 in] of the fusion line. Details of testing should specify the CVN test specimen notch location and provide other details so that the fracture will sample the weakest part of the HAZ. Precise location of the CVN notch in the coarse grained area requires a high degree of metallographic skill and is extremely difficult under the best of conditions.

C-7.5 Welding Consumables

C-7.5.1 WPS Requirements for Consumables. The code accepts the AWS classification of bare (not coated with flux), solid, steel welding electrodes on the basis of chemical composition. Solid steel electrodes are accepted by the code without regard to the manufacturer's name or brand. Fluxes and FCAW electrodes are considered individual products based on manufacturer's brand and type, regardless of AWS filler metal classification. Operating characteristics of these types of products may vary between manufacturers, even though generically classified the same. "Manufacturer" means the actual producer of the electrode or flux, not the supplier or the distributor.

Pure, single element shielding gases and accurate mixtures of shielding gases may be considered generic and are not subject to requalification due to a change in the gas producer. Gases used to shield FCAW, GMAW, or EGW are usually a single gas or a proportioned gas mixture, e.g., 75% CO_2 and 25% Ar. To minimize qualification testing for minor changes in the total mixture, Table 7.4, Note a does not require requalification unless a change in the minor element exceeds 25%. A 25% change of a 20% minor element is only a 5% change in the total mixture.

C-7.5.2 Active Flux. Active fluxes are those that contain small amounts of manganese, silicon, or both. These deoxidizers are added to the flux to provide improved resistance to porosity and weld cracking caused by contaminants on or in the base metal. The primary use for active fluxes is to make single-pass welds, especially on oxidized base metal. Since active fluxes do contain some deoxidizers, the manganese, silicon, or both in the weld metal will vary with changes in arc voltage. An increase in the manganese or silicon increases the strength of the weld metal in multiple pass welds. For this reason, voltage is more tightly controlled for multipass welding with active fluxes than when using neutral fluxes.

Neutral fluxes, in contrast, are those that will not produce any significant change in weld metal chemical analysis as a result of a large change in the arc voltage, and thus, the arc length. The primary purpose for neutral fluxes is in multiple pass welding, especially when the base metal exceeds 25 mm [1 in] in thickness. Since neutral fluxes contain little or no deoxidizers, they rely on the electrode to provide deoxidization. Single-pass welds with insufficient deoxidization on heavily oxidized base metal may be prone to porosity, centerline cracking, or both.

While neutral fluxes do maintain the chemical composition of the weld metal even when the voltage changes, it is not always true that the chemical composition of the weld metal is the same as the chemical composition of the electrode used.

A third type of flux is alloy flux that is distinctly different than either active or neutral flux. Alloy fluxes are those that can be used with a carbon steel electrode to make alloy weld metal. The alloys for the weld metal are added as ingredients in the flux. They are commonly used for welding weathering steels.

The code restricts the use of active fluxes to single and two pass applications, unless there is specific qualification under 7.12.4 and approval by the Engineer. For these limited pass applications, the extra level of deoxidizers make the flux the preferred choice of many Contractors. However, when extended to welds of three passes or more, problems may be encountered as the alloys of silicon and manganese can accumulate and contribute to cracking. To use active fluxes for large multipass welds, electrodes of low carbon, low silicon, and low manganese content (typically EL12) are used, and voltage needs to be carefully controlled.

Active fluxes are generally not used to make large multipass welds. The amount of alloy picked up from the flux is influenced primarily by the arc voltage. The 25 mm [1 in] test plate is considered adequate for this test because of the code's limitation on active fluxes to one and two-pass welds, unless approved by the Engineer.

C-7.6 Test Plate Thickness

Previous editions of the code have required WPS qualification on two thicknesses of steel, depending on the thickness of the material to be joined in production. This qualification requirement was based on an assumption that differences in cooling rates would result in differences in mechanical properties such as yield and tensile strength, ductility, and toughness. The thicker plates were expected to generate higher cooling rates, resulting in higher strength levels and lower ductility values. Thin plates were expected to have just the opposite effect on strength and ductility, and also expected to result in lower toughness values.

WPSs have been qualified by this method since the *Bridge Welding Code* was first issued in 1988, and two different plate thicknesses were used in the 1978 AASHTO Fracture Control Plan. The data from these tests were used to build a table that allowed for comparison of actual values obtained from essentially identical WPSs, but performed with different plate thicknesses. The changes in yield and tensile strength, while generally predictable, were negligible. Acceptable ductility values were obtained in all cases. The average yield strength for the slower-cooling thinner-plate specimens was 94% of the thicker-plate values. The average tensile strength of specimens from the thinner plates was 99% of that associated with the thicker plate.

With nominally identical WPSs, and test plate thickness as the only variable, CVN test values were affected to a greater extent than the tensile strength and elongation values, but no uniform trend was seen. In some cases, higher values were obtained for the CVN values under test conditions that involved thick plates while in other situations, the thinner plates had better values. This was deemed to be due to other variables than the cooling rate.

Frank and Abel evaluated several hundred PQRs and found that plate thickness, as well as a variety of other essential variables described in the code, did not serve as a good predictor of the probable mechanical properties. Further work done by Medlock and Frank further identified the lack of actual trends for these essential variables, despite the fact that some theoretical basis exists suggesting they are important.

After analyzing this data, and after considering the economic implications of continuing to mandate two plate thicknesses be used to qualify the full range of thicknesses that could be used in production, the subcommittee decided to standardize all WPS testing on one plate thickness. In doing so, some confusion that existed regarding the required plate thickness for certain applications was eliminated.

Although the code does not require that WPS qualification be performed on the actual thickness of steel that would be used in production, differences between the thicknesses of steel in production and that qualified by test do affect properties. Thicker steel will result in higher cooling rates, all other factors being equal. However, the code mandates higher levels of preheat with thicker steels. Applications involving thick sections are more highly restrained, although it has never been recommended that the qualification test plates duplicate the restraint that would be seen in actual applications.

C-7.6.1 Early editions of this code required two different test plate thicknesses, but practice demonstrated that there was no appreciable difference in test results at different thickness for these processes. ESW WPS qualification requires different test plate thicknesses as ESW makes the weld in one pass and the welding parameters used depend on the plate thickness. Additionally, the mechanical properties for ESW may vary significantly with different plate thicknesses.

C-7.7 General Requirements for WPS Qualification

C-7.7.1 WPS Qualification Test. This provision directs the code user to the options available for welding procedure qualification testing, including permitting the qualification of single pass fillet welds without a groove weld test.

In Figure 7.1, control of the direction of rolling is optional, although the mechanical properties, especially ductility, of the steel plate may vary significantly with the direction of rolling and may affect the test results. Unless cross rolling is used, tensile strength and impact toughness are often greater in the rolling direction than in the transverse direction. Using the rolling direction shown often gives better results in bend tests.

C-7.7.2 Pretest. The WPS pretest is identical to the WPS qualification test described in 7.7.1, except that the test is performed by someone other than the Contractor, and the test is performed under the provisions of 7.12 to establish limits on welding heat input.

The intent of the pretest approach to qualification is that one entity, such as a filler metal manufacturer, could conduct initial qualification of a WPS, and then the fabricator could complete qualification by simply conducting a verification test. However, in practice, this option is not commonly used as the verification includes the expensive and time-consuming elements of an actual qualification test, and therefore does not offer a particular advantage over the "full" test.

C-7.7.3 Verification of Pretest PQRs. The WPS verification test described using Test Plate B, Figure 7.2, is a simplified and less expensive form of mechanical testing. Verification tests are only performed when the Contractor has used pretests (WPS qualification tests conducted by others) as a basis for writing the WPS. Verification tests verify that the Contractor can produce the required results when following a WPS based on a PQR provided by another party.

C-7.7.5 Joints Not Conforming to Figure 4.4 or 4.5. Contractors are encouraged to use joint details that minimize shrinkage, distortion, and residual stress, especially when shrinkage stresses to members in the transverse "Z" direction may cause lamellar tearing. This may be done by redesigning the joint to reduce the required weld volume. The joint details described in Clause 4 are suitable for most routine welding applications, but may be improved upon when necessary, especially for large groove welds in heavy sections.

The root opening and the included angle of groove welds should be as small as possible, yet provide adequate access to achieve sound fusion when welded (see C-4.1.2 and C-5.4). Test Plate C, Figure 7.3, is designed to evaluate weld soundness, with the required mechanical properties, when following an approved WPS to weld proposed nonstandard joint details.

When welding is performed following a given WPS, changes in the joint geometry require changes in the number of weld passes in proportion to the difference in weld volume. Because of the groove angles used, weld volume increases at a rate higher than the rate of weld thickness increase. Changes in the same joint detail do not require requalification of the WPS if the only WPS change is to fill more or less volume.

The bend and tensile tests specified verify that good fusion has been achieved between the weld metal and the base metal and between the weld metal and any previously deposited weld passes.

C-7.7.6 Aging. "Aging" or "artificial aging" consists of a postweld thermal treatment whereby the test specimens are allowed to be heated to temperatures of 95 °C to 105 °C [200 °F to 220 °F] for up to 48 hours before mechanical testing. Aging involves the release of hydrogen after welding has been completed.

Artificial aging of qualification test welds or weld test specimens is specifically prohibited by the code, unless the production bridge welds represented by the testing are required to receive the same treatment. Hydrogen diffuses from welds and HAZs into the atmosphere over time. Small specimens with short travel distances for hydrogen to escape require a relatively short time period for hydrogen to release. Considering the time required to machine test specimens and prepare them for testing, a specimen that fails testing as a result of hydrogen may demonstrate that the WPS is not suitable for bridge construction.

Deliberately delaying testing to naturally age test specimens at room temperature, although not prohibited, should not be necessary to pass standard WPS tests.

C-7.7.7 It is routine practice to combine various welding processes and WPSs within one weld joint. For example, tack welds may be performed with SMAW and production welds made with SAW. In general, the mechanical properties of welds that are a combination of those deposited by various WPSs are not significantly changed, and therefore no testing of the combination is required.

C-7.7.7.1 The shielding system associated with FCAW-S is unique from that applied to other welding processes. While FCAW-S can be interchanged with other FCAW-S weld deposits without major changes to mechanical properties, such is not the case when non-FCAW-S weld deposits are combined with FCAW-S. Research has shown that yield, tensile, and elongation properties may be minorly affected, but the Charpy impact toughness may be significantly changed, depending on the specific welding processes and electrodes that are intermixed. Such changes can occur when the substrate is FCAW-S and the subsequent passes are non-FCAW-S. In addition, this behavior has been observed when the substrate is non-FCAW-S and the subsequent passes are FCAW-S. Therefore, for the specific situation where FCAW-S is combined with other processes, regardless of the sequence of welding, the same sequence that will be used in production must be qualified by tests. The influence is most dramatic in areas of the highest level of dilution, and hence the requirement that the tensile coupons and Charpy impact bars be extracted from an area of high intermix. Undiluted weld properties are evaluated in standard qualification tests.

FCAW-S deposits can be interchanged with other FCAW-S deposits without requiring WPS qualification testing because changes are minimal.

C-7.7.8 It is not the intent of this code to require all qualification tests to be redone every time a new edition is issued.

C-7.7.9 Qualification of undermatching weld metal will be done with the undermatching filler metal and the higher strength base metal to be used in production.

C-7.8 Position of Test Welds

C-7.8.1 Qualification Requirements. All WPSs are qualified for the position(s) in which they will be operated. Different welding positions may require different welding parameters, techniques, electrodes, and in some cases, equipment. Most high heat input WPSs are suitable for welding only in the flat and horizontal welding positions, although high heat is also used when welding vertical up. Changes in welding position have a major effect on welding travel speed and current. The resulting heat input and cooling rates are changed dramatically, significantly affecting the mechanical properties of the weld and HAZ.

C-7.8.2 Groove Weld Test Positions. An exception is made to allow test welds made in the flat position to also be considered for qualification of the horizontal position. This exception is allowed for groove weld positions and may also be considered to qualify fillet weld WPSs. This exception, however, does not extend to the fillet weld soundness test (see 7.10.3).

C-7.8.2.2 Position 2G (Horizontal). WPS qualification tests performed in the flat position also serve as qualification for horizontal. Most fillet welds are made in the horizontal position, and the WPS qualification using a groove weld is applicable to qualify flat and horizontal fillet welds.

C-7.8.2.3 Position 3G (Vertical). Typical vertical-down WPSs may produce the least amount of welding heat input. Vertical-down WPSs are qualified by testing approved by the Engineer (see 6.6.8 for SMAW and 6.13.1.7 for GMAW and FCAW).

C-7.9 Options for WPS Qualification or Prequalification

Groove weld WPSs not meeting the dimensional requirements of Figure 4.4 or 4.5 are required to be qualified using the Production Procedure WPS test of 7.12.4, regardless of welding process and filler metal. Test Plate C, Figure 7.3, is also required to be welded and tested to evaluate the joint configuration and soundness of the weld (see 7.7.5).

Fillet WPSs, with the exception of those prequalified in accordance with 7.11, are required to be qualified using a PQR from a satisfactory groove weld WPS qualification test or pretest. For groove welds made using filler metals listed in Table 6.1, a Maximum Heat Input test, Maximum-Minimum Heat Input test, or Production Procedure WPS test may be used. For ESW and EGW processes, and the SMAW process with high strength electrodes listed in Table 6.1 for Grade HPS 690W [HPS 100W], only Production Procedure WPS tests may be used. In addition to the mechanical properties testing of the groove weld WPS qualification test, a fillet weld soundness test using a Figure 7.8 detail is required (see C-7.10.3).

C-7.10 Fillet Weld WPS Qualification

C-7.10.1 Exemption from Groove Weld Qualification for Fillet WPS. Editions of this code prior to 2015 required mechanical testing of groove welds for qualification of fillet procedures (unless the WPS was prequalified). This is no longer required for WPSs that will be used to make only single-pass fillet welds.

Groove weld PQRs do not represent the mechanical properties of single-pass fillet welds well and do not reflect the ability of the WPS to produce fillet welds that meet this code. Groove weld test plates are typically made with many stringer weld passes. In these welds, each weld pass reheats previously deposited weld metal and thereby refines weld metal grains. The configuration of the WPS qualification test plate as shown in Figure 7.1 is such that it will have minimal base metal dilution. In contrast, single pass fillet welds have no such refinement, and most fillet weld passes tie directly into base metal.

More critically, use of a groove weld test has been detrimental to use of preferred fabrication practices. Though filler metal manufacturers have products uniquely suited to improving fillet welds, some do not perform well in groove welds. Hence, fillet weld procedure qualification by soundness testing, coupled with predictable consumable and base metal properties, facilitates both quality and productivity in bridge fillet welding.

C-7.10.2 Fillet Weld Mechanical Property Test. The mechanical properties of single-pass fillet welds and single-pass groove welds are not accurately predicted by the groove weld tests in Figure 7.1, but multiple-pass fillets do share some common characteristics with groove welds. For that reason, multi-pass fillet WPSs require validation by groove weld PQRs. Additionally, their quality is evaluated by macroetch testing required in 7.10.3.

C-7.10.3 Fillet Weld Soundness Test. Fillet weld soundness tests are simple to accomplish and demonstrate the capability of a procedure to achieve proper fusion, resistance to cracking, and a good profile. Following these provisions and Table 7.6, the fillet weld soundness test will closely resemble production fillet welding in the shop. Previous editions of the code limited testing to the maximum size single pass and minimum size multi-pass production fillet welds in each position. However, given the typically small variety of fillet welds used, the importance of good technique for each size and position, and the relative simplicity of soundness tests, the code shifted to requirements that are more practical and representative of shop practice. Because bridge fillet welds have performed very well over time, tension or toughness testing of fillet welds is not required.

C-7.11 Prequalified WPS

The SMAW filler metal tests conducted by manufacturers or other parties as required by the filler metal specifications are assumed to adequately represent the properties of low-hydrogen medium strength SMAW welds when they are used within manufacturer's recommended limits. Additional testing is not required provided these limits are observed. Extensive experience has proven such WPSs are acceptable. SMAW has a record of proven service performance over a wide range of WPSs for the steels listed.

C-7.11.1 Prequalified Tack Weld WPS. The mechanical properties of tack welds that are subsequently remelted using SAW would not significantly affect the performance of the weld or joint, only the chemical composition of the deposited SAW weld. With the exception of FCAW-S tack welds, the chemical composition of welds deposited using approved filler metals do not significantly affect the properties of the SAW deposit (see C-7.7.7). All other requirements for welding also apply to tack welds, including preheat, unless remelted using SAW (see C-5.3.7.1).

This provision applies only when tack welds are completely remelted by subsequent SAW. When the tack welds are not remelted by SAW, or when the tack welds are welded on by any other process, whether remelted or incorporated into the final weld, WPS qualification testing of non-SMAW tack welding WPSs is required.

In many situations, tack welds tend to be very small welds that naturally involve low levels of heat input. When these tack welds are remelted, the potentially harmful effects of the low heat input weld are effectively eliminated due to the remelting by the subsequent weld. This is not the situation, however, when the tack welds are incorporated into the final weld (e.g., not remelted). Tack welds that are not remelted should be treated as a regular production weld that is incorporated into the final weld. This involves qualification testing, and conformance to all the other code requirements. If a Contractor attempts to qualify a low heat input WPS that is used for tack welding, it is unlikely that the required mechanical properties and soundness will be achieved in the qualification test. When tack welding utilizes welding parameters that are similar to typical WPS welding, achieving the requirements for WPS qualification is more readily accomplished, and the production welding is of the appropriate quality.

C-7.12 Heat Input Qualifications

Heat input, sometimes called energy input, is a measure of the amount of electrical energy that is associated with the welding arc. If 100% of the electrical energy were converted to thermal energy, and if 100% of the thermal energy were transferred to the weld deposit, heat input could be used to directly compute cooling rates that occur in the weld and the HAZ. However, not all of the electrical energy is converted directly to thermal energy, and not all of the thermal energy is transferred to the weld deposit. Some of the electrical energy is converted to visible light, noise, etc. Some of the thermal energy is not transferred to the weld deposit, but rather results in the vaporization of metals, generating fume. Some energy is used to melt slag. Most of the energy used to heat and melt the electrode is ultimately introduced into the weld through the hot metal droplets, although some is lost through spatter. For theoretical work, an efficiency factor is often added to the heat input equation to account for these losses. This is not done in the code because it would have no particular effect on how heat input is used for control of WPSs.

Heat input is used to combine the variables of current (amperage), electrical potential (voltage), and travel speed into one term. The same inaccuracies that exist in the computation of heat input also occur in both WPS qualification testing and in production, minimizing the effect of these inaccuracies. Numerically equivalent computed values of heat input for SAW and SMAW, for example, may have significant differences in the actual thermal energy delivered to the weld deposit. SAW transfers a significant portion of the computed electrical energy into the weld deposit as thermal energy since it does not involve an open arc that generates visible light, large levels of fume, or high levels of heat conduction to the atmosphere. Some thermal energy in SMAW is lost when hot weld stubs are discarded. Differences between welding processes have little consequence in the application of the code, however, because WPS qualification is based on each welding process.

Heat input is approximately proportional to the cross-sectional area of the individual weld bead deposited. Small weld beads will be associated with lower levels of heat input, and larger individual weld passes will naturally result in higher levels of heat input. The heat input associated with fillet welds is proportional to the square of the leg size (see Annex F, Figure F.4). Single-pass fillet welds of a given size are therefore closely linked to a specific heat input for a given welding process.

For a given WPS qualification, the type of electrode, solid or cored, does not change. Solid electrodes are of the same AWS classification. FCAW electrodes, SAW flux, and shielding gas or gas mixture are of the same classification, manufacturer's brand and type. Current type, polarity, and electrode extension all remain the same, except that electrode extension may vary by less than 20 mm [3/4 in] in SAW or 6 mm [1/4 in] for FCAW-G without requiring requalification (see C-7.12.1.3).

A ±10% variation in calculated heat input among passes is allowed in order to provide some flexibility, and with automated equipment or active monitoring and adjusting for semi-automatic procedures, it is possible to satisfy that limit for test groove welds. Exceptions are made for root and cap passes to facilitate good workmanship and because these passes, being at the very top and bottom of the weld, will have a negligible effect on weld specimen properties and test results.

C-7.12.1 Maximum Heat Input Qualification Test. Excessively high welding heat input often reduces weld metal toughness; therefore WPSs need to be qualified by testing at the maximum welding heat input, and production welding is controlled so that test parameters are not exceeded. With this testing method and production control, the welds that are produced should possess the required strength, ductility, and toughness, regardless of the combination of variables used to compute the heat input. Weld soundness, however, may be affected.

Care should be taken to prevent the buildup of interpass temperature beyond the maximum expected in the work as weld metal strength and toughness may deteriorate at excessively high interpass temperatures. Placing a jet of compressed air behind the joint between passes is allowable, but experience has shown that this acceleration of cooling can lead to unacceptable strength levels and deteriorations in notch toughness. This practice should never be employed in production, and even though allowed for the qualification test plates, should only be done with caution and knowledge. A preferred method of temperature control is to wait for the test plate to cool between weld passes.

C-7.12.1.2 Electrodes. There are practical limits to how little or how much current can be conducted by electrodes of various diameters. Since welding current as measured by amperage is an essential variable, the practical limits of electrode diameters are indirectly regulated. Small changes in the electrode diameter do not result in significant changes to the weld properties or weld soundness, all other variables being equal. Therefore, electrode diameter is not an essential variable in this method. Significant electrode diameter changes may, however, change the weld bead shape and may affect weld soundness.

The number of welding electrodes being operated simultaneously has a major effect on the WPS and therefore is included as an essential variable. The diameter of the electrode(s) is less important in this method of qualification testing because it is based on welding heat input. Operating current generally is increased with an increase in electrode diameter. High currents can be obtained by operating small electrodes at high wire feed speed rates, and relatively lower currents can be obtained by operating large electrodes at slower wire feed speed rates. The code allows current to be controlled by controlling the wire feed speed (see 6.29).

C-7.12.1.3 Electrical Parameters. Welding parameters can be controlled with either wire feed speed or amperage. In a constant voltage system, an increase in wire feed speed results in an increase of current, all other conditions being equal. Although some welding equipment may contain an adjustment mechanism that indicates that welding current is being controlled, such controls simply regulate the speed at which the electrode is delivered to the arc. Current is dependent on the welding polarity, electrode diameter, and electrical stickout, in addition to the wire feed speed. Controlling wire feed speed is a more precise method of controlling welding parameters, although some equipment is not capable of directly reading wire feed speeds. For computation of heat input, current is still required, and conversion charts are available to correlate current to specific wire feed speeds. It is essential that the correlation considers the effects of polarity, electrode diameter, and electrode extension (see 6.29).

Current type may be either alternating current or direct current, AC or DC. Polarity is the sign of the current, electrode positive or electrode negative, and determines the direction of the flow of electrons across the arc. For a given wire feed speed, operating arc welding equipment DC electrode positive, frequently referred to as reverse polarity, produces deeper penetration than DC negative. For a given wire feed speed, DC electrode negative, also called straight polarity, produces shallower penetration than DC positive. AC changes polarity 120 times per second, and therefore depth of penetration is between the two.

The electrode extension, also called stickout, is defined as the distance from the end of the contact tip to the start of the arc. However, from a practical point of view, electrode extension is often measured between the contact tip and the work. Either approach is allowable provided it is consistently applied in both qualification testing and production. A significant increase in electrode extension will result in a decrease in welding current if the wire feed speed is unchanged. With increased electrode extension, the electrode is heated by electrical resistance, raising the temperature of the electrode and reducing the necessary amperage to melt the electrode. There is a significant voltage drop across the electrode extension, and in order to maintain an adequate arc voltage, the voltage is increased to compensate for this drop. Although the welding current decreases for a given wire feed speed, if the travel speed is maintained constant, the heat input of welding does not decrease as significantly as the decrease in current because there is an increase in voltage. The code allows variation in electrical stickout of up to 20 mm [3/4 in] for SAW, and 6 mm [1/4 in] for FCAW and GMAW without requiring requalification. Changes that exceed this range require requalification.

The electrical resistance supplied by the electrode is largely dependent on the cross-sectional area that conducts the electrical current. For solid electrodes, the entire cross section can be used to conduct current. For FCAW electrodes, the current is primarily carried by the electrode sheath. Therefore, for a given diameter of electrodes, the electrical resistance for a FCAW electrode is significantly greater than that for a solid electrode. For larger diameter electrodes, the resistance is less than that associated with smaller diameter electrodes. Since FCAW-G typically uses smaller diameter electrodes than SAW, and always uses FCAW electrodes, small changes in the electrode extension, the length of electrode subject to heating, may have a significant effect on electrode heating. In contrast, SAW with larger diameter, solid electrodes will be affected to a lesser extent. Therefore, changes in electrical stickout that require requalification are more restrictive for FCAW-G than for SAW.

Electrode extension is an essential variable only for the wire-fed welding processes. It has no applicability to SMAW.

C-7.12.1.4 Maximum Current. The maximum heat input WPS qualification method determines the maximum heat input that can be used in production welding. Heat input is mathematically calculated from the welding current (measured in amperage), welding voltage, and travel speed. For example, a WPS may be qualified with a maximum heat input using the following parameters: 30 volts, 300 amperes, and 300 mm/minute travel speed, yielding the computed heat input of 1.8 kJ/mm. A welding procedure that uses 30 volts, 400 amperes, and a travel speed of 500 mm/minute results in 1.44 kJ/mm, which is a lower heat input even though it has a higher amperage. Hence, the amperage shown on the PQR does not need to be the maximum amperage used in production. This is a significant change from pre-2015 editions of the code.

Table 7.12 provides current limits for the various electrodes. Fabricators may operate outside of these limits if they choose, but only if they qualify the welding procedure under the production method—the fabricator may not use the heat input method to qualify procedures with amperages outside of the values shown in Table 7.12. This special limitation sets reasonable and practical boundaries on how far the fabricator may stray from the qualified settings—for example, a fabricator could not run a qualification test at a given amperage and travel speed and then increase the amperage outside the limits of Table 7.12.

For electrode sizes not shown in Table 7.12, the maximum and minimum current limits can be determined by linear interpolation. The average current for the next smaller and next larger electrode size is divided by the average of the next smaller and next larger electrode size, and then multiplied by the unlisted electrode size.

C-7.12.1.5 Maximum Voltage. As with amperage, the voltage shown on the maximum heat input PQR does not need to be the maximum used in production, nor does the travel speed need to be the minimum. Rather, the computed heat input, based on the amperage, voltage, and travel speed used in production, may not exceed the maximum heat input shown on the PQR.

The root and cap passes are exempt from the voltage calculation because the weld metal from these passes is not incorporated into the all-weld metal tensile tests and CVN specimens; thus, it is not evaluated in those qualification tests.

The voltage of interest is the voltage between the contact tip and the workpiece, not the total system voltage that includes voltage drops across welding leads and work (or ground) leads. Power source meters typically read total system voltage and should not be confused with the voltage between the contact tip and work. It is possible, for example, to use higher system voltages in production than those utilized for the qualification test plate, provided the production voltage from the contact tip to the work is equal to or less than the same voltage as measured during the performance of the qualification testing. Contact tip to workpiece voltage may be measured directly when using automatic welding processes, but would be difficult with semiautomatic processes. Commonly for both automatic and semiautomatic welding, voltage is measured from wire feeder to workpiece.

An increase in arc voltage will increase the amount of alloy absorbed from SAW alloy or active fluxes (see Clause 3 and C-7.5.2 for the definition of active, alloy, and neutral fluxes). The most common elements picked up from voltage sensitive active SAW fluxes are manganese and silicon. Active fluxes are restricted to one and two-pass welds, unless approved by the Engineer (see 7.5.2). Active flux used with relatively high manganese, high silicon electrodes and operated at high welding voltage may increase the amount of manganese and silicon in the weld to unacceptable limits, causing the weld to be hard and brittle. Alloy fluxes are not, by definition, active fluxes, but the alloy elements, principally nickel and chromium, absorbed from the flux, generally do not build-up to unacceptable limits. Alloy fluxes may be used to make multipass welds without the approval of the Engineer (see 7.5.2 and C-6.8).

C-7.12.1.6 Minimum Gas Flow. The shielding gas flow rate is specified to be the minimum allowed by the WPS, to evaluate the effect of minimum shielding on weld soundness and mechanical properties. Minimum flow rate will also minimize weld cooling, but this variation has little effect.

C-7.12.1.7 Travel Speed. Slowing travel speed while maintaining the same amperage and voltage increases the calculated heat input, but the PQR travel speed does not need to be the minimum to be used in production. Rather, the calculated heat input as determined from the amperage, voltage, and travel speed used in production cannot exceed the PQR heat input maximum.

C-7.12.1.8 Preheat and Interpass Temperature. This provision was significantly changed in the 2002 edition of this code. Before 2002, preheat and minimum interpass temperature were dictated by production welding. This created the occasional conflict when a WPS qualified with preheat values of Table 6.3 conflicted with values described in Clause 12. To ensure uniformity between the WPS qualification conditions for WPSs used for redundant and nonredundant work, the minimum preheat and minimum interpass temperatures were changed to be specific values. Thus, all WPS qualification tests now use the same preheat level.

The expectation of the maximum heat input test is that low cooling rate conditions would be developed. Therefore, the preheat value is set at a relatively high level to facilitate slow cooling. Production preheat should be as determined by the tables in Clause 6 or 12, as applicable.

C-7.12.1.9 Maximum Interpass Temperature. After welding has begun, the interpass temperature on a small test specimen will begin to rise. During the WPS qualification test, the interpass temperature should be allowed to increase until the maximum value of interpass temperature is achieved. During the WPS qualification test, the interpass temperature should be maintained below the maximum interpass temperature shown on the WPS to avoid adversely affecting the weld metal toughness measurement from the test. Allow the plate to cool between passes so that the maximum interpass temperature desired for the WPS is not exceeded. It is then possible to allow the plate to cool between passes so that the maximum interpass temperature desired for the WPS is not exceeded. The Maximum WPS value to be used in production will be determined by the maximum heat input test.

C-7.12.2 Maximum-Minimum Heat Input Qualification Test. The Maximum-Minimum Heat Input test was developed to minimize the required number of qualification tests. The high heat input portion evaluates WPSs that may result in low CVN test values or low yield and tensile strengths. The low heat input portion evaluates WPSs that may have a greater incidence of fusion discontinuities or higher hardness that may adversely affect soundness and mechanical properties. The filler metals listed in Table 6.1 have a long history of satisfactory performance and are expected to perform well in bridge construction if qualification tests at both high and low welding heat inputs verify conformance to code requirements (see 6.27 and 6.29 for control of welding variables during production welding).

Care should be taken when welding any heat-treated steel, particularly quenched and tempered steels, to ensure that the maximum heat input from welding does not exceed the steel manufacturer's recommendations. Excessive heat input may lower the toughness of the HAZ.

For the maximum-minimum heat input test method, the maximum heat input test is conducted in exactly the same manner as would be done if only the maximum heat input test were conducted in conformance with 7.12.1. Only the minimum heat input test is additionally required.

The low heat input tests verify that welding at the minimum heat input to be used in the work will produce sound welds, free of cracks, that have the required strength, ductility, and toughness. Because test plates are significantly smaller than typical bridge girder flanges, these become hotter from the welding and heat more rapidly. The interpass temperature will be monitored and limited so that test plate temperatures approximate the minimum preheat temperature.

The goal of the minimum heat input test is to create welding conditions that are representative of the highest cooling rate that would be encountered using that particular WPS. The minimum preheat and interpass temperatures are to be used in testing, along with minimum heat input levels, creating some practical problems.

C-7.12.2.1 This subclause clarifies that the maximum and minimum heat input values are based on the average heat input reported on the PQR—and not, for example, the highest pass or lowest pass. Successive subclauses also clarify that the qualification amperage, volts, and travel speed do not need to be the same as those used on the floor (since they are controlled by conformance with heat input maximum and minimum limits). However, amperage must be within the limits of Table 7.12.

C-7.12.2.1(1) See C-7.12.1.2.

C-7.12.2.1(2) See C-7.12.1.3.

C-7.12.2.1(3) See C-7.12.1.4 for current interpolation discussion.

C-7.12.2.1(6) For the minimum heat input test, a high cooling rate is the objective. To ensure that this high cooling rate occurs, the preheat for the test plate is between 10 °C and 40 °C [50 °F–125 °F]. If the test plate is below 10 °C [50 °F], it can be warmed to a temperature not to exceed 40 °C [125 °F]. 40 °C [125 °F] was selected to ensure that artificial cooling of the plates would be unnecessary under most conditions.

C-7.12.2.1(7) The goal of the minimum heat input test is to achieve a rapid cooling rate. The interpass temperature has a specific maximum value to ensure that high cooling rate conditions are achieved. This value is imposed on the test only, and need not be applied to production welding. It is possible to artificially cool the test plate between passes although such cooling may negatively affect the obtained test results.

C-7.12.3.1 Maximum Heat Input Envelope. Limited changes, as allowed in 7.12.3.1 and 7.12.3.2, are not expected to have any adverse effect on required weld metal properties. To minimize WPS qualification testing, the Contractor may test with only the maximum welding heat input condition intended for use, then operate the welding equipment within 60% and 100% of the heat input of the tested WPS, as well as within the limitations on current and voltage within this subclause. Travel speed is not specifically limited by this method. However, the highest travel speed that can be employed may be computed by taking the lowest heat input allowable (60%) and the highest current and voltage allowable (100%), computing that the highest allowable travel speed will be 1.66 times the tested parameters. This maximum value of travel speed may only be used with the maximum amperage and voltage allowed. Similarly, the minimum allowable travel speed may be determined with the use of the maximum heat input (100% of that tested) with the minimum allowable current (80%) and minimum voltage (86%), resulting in a minimum travel speed of 69% of that tested.

C-7.12.3.2 Production WPS Current, Voltage, and Travel Speed. This subclause establishes the allowable variance that can be used for amperage, voltage, and travel speed in writing production procedures that have been qualified by the maximum heat input method (see 7.12.1). Provided the heat input is within the window of 7.12.3.1, the only other limits are that amperage must be within the Table 7.12 limits and voltage can vary by ±10%. There are specific voltage limits because large changes in voltage can significantly affect final chemical composition when alloy and active fluxes are used.

C-7.12.3.3 Production Current, Voltage, and Travel Speed. This subclause establishes the allowable ranges for amperage, voltage, and travel speed in writing production procedures qualified by the Maximum-Minimum Heat Input method (see 7.12.2). Provided the heat input is within the window of 7.12.3.4, the only other limits are that amperage must be within the Table 7.12 limits and the voltage limits shown. As with the Maximum Heat Input method, there are specific voltage limits because large changes in voltage can significantly impact final chemical composition when alloy and active fluxes are used.

C-7.12.3.4 Maximum-Minimum Heat Input Production Limits. When the Contractor plans to operate WPSs qualified in conformance with the provisions of 7.12.2 over a range of welding heat inputs, the highest and the lowest welding heat inputs are usually qualified in separate tests. High heat input may adversely affect toughness, strength, and soundness. Low heat input may adversely affect toughness, soundness, or ductility. If the tests of the WPSs that represent the upper and lower heat input limits produce satisfactory results, the Contractor may write and use WPSs that operate anywhere between the maximum and minimum heat input limits, staying within the tested range limitations for voltage and the current production limits of 7.12.3.4. Travel speed may be adjusted without limitation to stay within the bounds of the tested heat input range.

Rather than conducting a Minimum Heat Input test, it may be advantageous to run a second Maximum Heat Input test using a lower nominal level for the maximum heat input. This approach can be effective in extending the lower bound of heat input with the second test.

C-7.12.4 Production Procedure Qualification. The premise of the production qualification method is that the settings to be used on the projects are actually tested, versus a range of settings being tested with the heat input methods. The fabricator may qualify WPSs with any of the listed methods. However, certain processes (as specified in the code) must be qualified using the production procedure method.

Qualification methods for ESW and EGW are similar to the production method, but they do not fully fall within the rules of 7.12.4. Rules for ESW and EGW procedure qualification are found in other parts of Clause 7.

C-7.12.4.2 Exceeding the variations allowed in Table 7.6 may affect the mechanical properties, chemical composition, or soundness of the weldment. These variables are referred to as essential variables, and are to be specifically listed in the WPS. Changes within the limitation of essential variables are permitted without requalification; changes outside these limits require requalification of the WPS.

In editions of the code prior to 2002, it was possible to qualify different values of preheat by conducting a Production Procedure Qualification Test that employed different preheat values.

It was subsequently determined that qualification of preheat values below the levels contained in Table 6.3, Table 12.4, 12.5, 12.6, 12.7, or 12.8, was *not* the intent. Therefore, changes were made to prescribe the preheat conditions for the Production Procedure Test. The values as contained in 6.2 are maintained for this test. Production preheat and interpass temperatures are governed by other code requirements.

C-7.13 Electrogas Welding

The WPSs to be used for EGW are detailed in Clause 6, Part E, and the essential variables for these procedures are given in Table 7.7.

C-7.13.1 Figure 7.1. Because most EGW WPSs use a square butt joint preparation, the test plates are prepared with a square edge. If another type of groove is being used in the joint, the groove in the test plate should match that in the joint. Eight specimens are required instead of five because the coarse columnar grain structure of EGW leads to much higher scatter in CVN test results.

C-7.13.2 Limitations. For variations in Filler Metal Oscillation only, full WPS retesting will not be necessary, but the weld made using a previously qualified WPS with revised oscillation values is to be examined using either RT or UT. The weld may be a production or test weld.

C-7.14 Electroslag Welding

The restrictions on production welding in Clause 6 are intended to provide adequate HAZ CVN toughness without depending on CVN testing of the HAZ.

C-7.14.1 Figure 7.1. Because ESW uses a square butt joint preparation, the test plates are prepared with a square edge. Eight specimens are required instead of five because the coarse columnar grain structure of ESW leads to much higher scatter in CVN test results.

C-7.15 Type of Tests and Purpose

Weld test plates are first visually inspected, then radiographed to ensure that the WPS is capable of producing sound welds that meet all the quality requirements of the code. If visual inspection or NDT indicates that the test weld contains unacceptable weld discontinuities, there is no need to machine test specimens and conduct tests because the WPS testing is still considered a failure. When acceptable weld discontinuities are very localized and there is sufficient weld length, it is acceptable to machine all required test specimens from areas of the weld that are defect free.

Acceptance of WPSs is based on satisfactory achievement of required mechanical values for strength, ductility, and toughness, and satisfactory quality as documented by NDT and destructive tests for soundness. WPS qualification testing verifies mechanical properties based on test welds. In production welding, soundness is also verified by visual tests and NDT.

C-7.15.1 Groove Welds. These tests evaluate the soundness of the weld metal and determine the mechanical properties of the deposited weld metal. If, in exceptional situations, a test joint is required to use undermatching weld metal or two different specified base metal strengths, the reduced section tensile tests and side-bend specimens will not result in meaningful mechanical examinations.

C-7.17 Nondestructive Testing (NDT)

All WPS qualification test plates are required to be radiographed to demonstrate soundness before mechanical testing, regardless of the welding process used. Additionally, NDT reduces the expense and delays that result from machining and testing welds having discontinuities prohibited by the code. UT is required in addition to RT for ESW procedure qualification because RT may not detect planar discontinuities (e.g., cracks, incomplete fusion) oriented parallel to the film or tight planar discontinuities, and UT of ESW test plates has been demonstrated to reveal workmanship defects as well as RT.

C-7.18 Method of Testing Specimens

C-7.18.1 Under some conditions, the tensile testing capacity of a laboratory may preclude the use of full-sized specimens. This is often the case when higher strength steels are used. Under these conditions, multiple specimens may be used. The entire thickness of the test specimen is tested.

C-7.19 Test Results Required

C-7.19.3.2 Undermatching. In code editions prior to 2020, qualification testing for WPSs using undermatched filler metal was required to be performed using the base metal listed on the WPS, and the WPS qualification was exempted from reduced-section tension and bend tests. In 2020, the qualification requirements were modified to require test plate base materials to be chosen to approximately match the strength of the filler metal; the base metal will not be the same material as will be used in production. This allows bend testing and reduced-section tensile testing of the sample weld. Because the undermatched weld metal will not match the strength of the production base metal, the WPS base metal is not the same as that used in the qualification test. Table 7.3 is used to determine the required properties as a function of the base metal used in the test.

C-7.19.4(1) The highest and lowest values are disregarded to exclude outlying data points, such as those due to a mis-performed test, that do not represent properties of the weld metal overall.

Part B
Welder, Welding Operator, and Tack Welder Qualification

The qualification tests are especially designed to determine the ability of the welders, welding operators, and tack welders to produce sound welds by following a WPS. The code does not imply that anyone who satisfactorily completes performance qualification testing can perform the welding for which he or she is qualified under all conditions that may be encountered during production welding. It is essential that welders, welding operators, and tack welders have some degree of training for these special conditions.

The welding personnel qualification tests are specifically designed to determine a person's ability to produce sound welds in any given test joint. After successfully completing the qualification tests, the welder should be considered to have minimum acceptable qualifications. Knowledge of the material to be welded is beneficial to the welder in producing a sound weldment, therefore, it is recommended that before welding quenched and tempered steels, welders should either be given instructions regarding the properties of this material, or have prior experience in welding the particular steel.

C-7.21 General Requirements.

Vision acuity is important for welders, welding operators, and tack welders to perform their jobs in an acceptable manner. Testing is not a guarantee that their vision will continue to remain satisfactory to produce acceptable welds. If it appears that an individual is having difficulty seeing properly, a vision acuity test should be performed.

C-7.21.1 Purpose. Welder qualification tests are intended to document the ability of a welder, welding operator, or tack welder to make sound welds by following a WPS provided by the Contractor. The test is intended to establish the ability of the individual (1) to adjust and control the equipment, (2) follow the WPS, (3) guide or manipulate the electrode to ensure sound fusion between the weld and the adjacent base metal or previously deposited weld pass, and (4) produce a weld that does not contain an unacceptable number or size of weld discontinuities such as undercut, overlap, porosity, and slag inclusions. Lack of fusion or other discontinuities caused by poor welding technique may cause the specimen to fail a bend test. However, if a sound weld has insufficient strength or lacks sufficient ductility to pass the bend test, it is generally not the fault of the welder, but may be the result of an inadequate WPS or poor test specimen preparation. Welder qualification tests are only intended to measure the skills that are necessary to produce weld soundness. All other properties of the weld are those determined by the selection of filler metal, base metal, and the WPS.

The code does not intend to require unnecessary duplication of effort. Where there is evidence that welding personnel have previously been qualified by tests described in this code and are current as described in 7.21.4, requalification should not be ordered unless there is some reason to question the skill of an individual.

C-7.21.3 Base Metal. The base metal used in welding personnel qualification testing does not affect the technique used by the welder, but may affect the physical properties of the weld and base metal during physical testing of the sample in bend testing. If an unlisted steel is to be welded, personnel welding on this steel qualify using test plates of the same specification, although not necessarily the same grade.

C-7.21.4 Period of Effectiveness. In order to verify the six-month limitation on welding personnel qualification, it is recommended that the Contractor maintain a record documenting compliance with this requirement. Although the code allows qualification to remain in effect indefinitely, some Owners place a limit on the length of time an individual may be considered qualified to weld without repeating qualification testing. Such requirements are discouraged. The code intends that there be no unnecessary duplication of effort. Where there is evidence that welding personnel are qualified by tests described by this code, and qualification is current as described in this subclause, requalification should not be necessary unless there is some reason to question the ability of an individual welder, welding operator, or tack welder.

C-7.21.5.1 Root and Fill Pass Cleaning. Personnel are not to be qualified if they cannot consistently make welds of proper profile and free of unacceptable discontinuities. Grinding and the other described actions would allow the correction of poor profile and the repair or removal of discontinuities in the test plate, allowing a welder with poor or unacceptable technique to, perhaps, pass the test.

Interpass cleaning is only to remove material other than weld metal, such as slag, oxides, etc. It is not intended to smooth the weld surface or eliminate visible weld defects. A powered wire wheel speeds the cleaning but should not be used with sufficient force or duration to remove metal from the weld surface.

C-7.21.6.1 Contractor. The Contractor is responsible for the qualification of welding personnel. The Contractor is not required to physically conduct the testing and may have the testing supervised and conducted by a third party, provided the Contractor verifies the adequacy of the third party testing.

C-7.21.7 Records. Qualification test records should contain information regarding date of testing, process, WPS, test plate, position, the witnessing Inspector's name, and the results of the testing.

C-7.21.8 Previous Code Editions. Welding personnel qualification tests conducted using either U.S. Customary or metric (SI) units of measurement are acceptable, and qualify the welder for work under both systems of measurement.

C-7.24 Limitations of Variables

C-7.24.1.1 Base Metal. Welders, welding operators, and tack welders welding quenched and tempered high strength steels should have experience welding such base metals. Because of the increased risk of cracking and the effects of welding on HAZ mechanical properties, welding personnel welding on Grade HPS 690W [HPS 100W] steel are to be tested on steel of the same specification, Grade HPS 690W [HPS 100W] steel as appropriate.

C-7.24.1.2 Process. FCAW-S and FCAW-G are considered the same process for welding personnel qualification.

C-7.24.1.3 Approved Electrode and Shielding Medium. Although a change in manufacturer within a given classification of filler metal, change of flux, or change of shielding gas is an essential item for WPS qualification, these are not factors in welding personnel qualification. Changes in these parameters affect the WPS, but will have an insignificant effect on the techniques used for welding.

C-7.24.2.1 SMAW Restrictions. The operational characteristics of E7018-type electrodes are essentially the same as other low hydrogen SMAW electrodes and therefore welding personnel are not required to be qualified with electrodes with other classifications. The exception to this is when E100 and E110 electrodes are used.

C-7.24.3.1 ESW/EGW. Although a change in manufacturer within a given classification of filler metal, change of flux, or change of shielding gas is an essential item for WPS qualification, these are not factors in welding personnel qualification. Changes in these parameters affect the WPS, but have an insignificant effect on the setup and operations used for these automatic welding processes.

C-7.24.4.2 Position. Unlike the position limitations for welder qualification in 7.22.1, tack welder qualification is position specific. A welder qualified for the vertical position is also qualified for the flat and horizontal positions. A tack welder qualified for the vertical position is not qualified for the flat and horizontal positions. Separate tests are necessary for each tack weld position.

C-7.26 Method of Testing Specimens

C-7.26.1 Radiographic Testing. With the single exception of GMAW-S, all welding personnel qualification testing may be done by either mechanical testing or RT of test welds.

GMAW-S is susceptible to a high incidence of fusion discontinuities called "cold laps." The guided bend tests used for welder qualification produce sufficient strain in the test specimens to cause cracking of cold lapped areas that may be missed by RT because of size or orientation.

Welder qualification testing by RT subjects the complete weld to the same test for soundness that is the basis for acceptance of bridge welds. Bend tests only measure the soundness of the half thickness of the weld test specimen that is subjected to tensile stress as the specimen is bent. Discontinuities on the inside, or compression side, of the bend are often not detected. RT can also evaluate the soundness of the root in welds made against fused steel backing. Achieving good fusion at the root is one of the more difficult parts of the test, and accurately reflects difficulty in construction. Bend tests often fail to properly evaluate small, but extensive, fusion discontinuities in the root because they are machined or ground away during preparation of the bend specimens.

Because test specimens do not have to be machined from the test weld, and because testing can be completed with much less lost time, welder qualification by RT may also be less expensive than bend testing.

C-7.26.3 Fillet Weld Break and Macroetch Test Requirements. The purpose of these tests is to determine the soundness of the fillet welded joint. The test acceptance is determined by the extent and nature of any discontinuities revealed by the rupture of the break specimen, should it occur, or the cut face of the macroetch specimen.

C-7.28 Retests.

These provisions are applicable during initial welding personnel qualification testing, and during testing because of loss of qualification from poor workmanship or qualification expiration. For requalification because of time limits, a limited qualification test on 10 mm [3/8 in] plate is used. For requalification because of poor workmanship, full testing is necessary, identical to testing for new welding personnel (see 7.21.4).

C-7.28.1.1 Immediate Retest. Upon failure of a welder or welding operator to pass the qualification test, if it is desired, the welder or operator may immediately weld two additional test plates. If both plates pass, then the welder or operator is considered qualified.

C-7.28.2 Tack Welder. Upon failure of a tack welder to pass the qualification test, if it is desired, the welder or operator may immediately weld an additional test plate. If this plate passes, then the tack welder is considered qualified. This is less restrictive than the welder and welding operator retesting provision, because only one test plate is used rather than two.

C-Table 7.3 Table 7.3 lists the required mechanical properties of yield and tensile strengths, ductility, and toughness for the tested weld metal. Each base metal strength and category is followed by a list of processes and appropriate filler metal classifications that are intended to produce weld metal with mechanical properties suitable for tension butt joints and other welds that require weld metal of matching strength, ductility, and toughness.

Previous editions of the code have had different Procedure Qualification Test acceptance criteria for different filler metals. Such criteria included minimum and maximum values for tensile strength, minimum yield strength values, minimum ductility values, and minimum Charpy values. This created some logical inconsistencies when the acceptance criteria were different for various filler metals, even though they were expected to be used on the same grade of steel in production. In order to provide technical consistency, it was determined that based on the steel grade being joined (minimum yield strengths, minimum tensile strengths, minimum elongation values, and minimum toughness values that were the same), all processes and filler metals for a given steel would have the same requirements. The required values were made a function of the steel that would be joined.

The maximum value for the tensile strength was deliberately omitted since the elongation value was expected to be sufficient to ensure that the deposited weld metal would have adequate ductility, and that higher strength weld metal would perform acceptably, provided the elongation and toughness criteria were satisfied.

C-Table 7.6 (1–4) Filler Metal Type. The provisions of 7.5.1 apply to qualification using any of the WPS qualification test methods, under 7.12.4. SAW is commonly qualified using the methods of 7.12 and are not subjected to the essential variable limits of Table 7.6. However, high strength SAW and SAW in nonstandard joints are qualified using 7.12.4, and these applications are subjected to the limitations of Table 7.6.

For SAW, each AWS filler metal classification of bare, solid electrode and each manufacturer's brand and type of cored electrode or SAW flux used require qualification (see C-7.5.1). SAW flux or metal additions that are used to significantly modify the chemical composition of the weld, or supplement the filler metal volume, or both, are essential variables. Alloy fluxes are used to make welds more corrosion resistant and may be used to modify mechanical properties. Additions of metal powders, or cut wire, to the SAW molten weld pool present complications in ensuring weld soundness and uniform weld metal properties. When the chemical composition or mechanical properties of the weld are dependent on metal additions, the use of these products constitutes an essential variable.

C-Table 7.6 (5) Electrode Diameter. A major difference between qualification under 7.12.1, 7.12.2, and 7.12.4 is that electrode diameter (size) is an essential variable in 7.12.4 but not in 7.12.1 or 7.12.2. A change of two or more standard diameters, as described in the AWS A5.XX electrode specifications, requires requalification if the Production Procedure WPS qualification test is used.

C-Table 7.6 (6) Number of Electrodes. A change in the number of electrodes used is an essential variable regardless of the method used to qualify WPSs. Changing from single to multiple electrodes, or vice versa, may significantly affect heat input and cooling rates.

C-Table 7.6 (7–13) Electrical Parameters, Travel Speed, and Heat Input. These provisions address changes in electrical controls that are considered essential variables, and also include travel speed that is not electrical, but is a factor in heat input. Electrical controls and travel speed, in combination, control welding heat input.

C-Table 7.6 (7) Amperage. The recommended current ranges provided by SMAW electrode manufacturers are usually quite broad, and it is typically difficult to weld outside these ranges. If satisfactory welds are being produced, it is generally taken as evidence that the current and voltage are acceptable. However, when it is known that the Contractor wishes to use current values beyond those recommended by the manufacturer of the electrode, qualification is required.

The Contractor specifies the current in the WPS. Variations exceeding the specified limits necessitate requalification. Current determines the electrode meltoff rate, and therefore the volume of individual weld passes for any given travel speed. Electrode extension or contact tube to work distance is an important welding variable that affects the current as well as the transfer mode. At a given wire feed speed, using a constant-voltage power source, longer electrode extensions cause the welding current to decrease. This may reduce weld penetration, heat input, and cause fusion discontinuities. Shorter extension causes an increase in welding current. For machine operation, electrode extension may be premeasured; for manual welding, it is visually estimated. See C-7.12.1.2 and C-7.12.2.1(1).

C-Table 7.6 (9) Mode Transfer. The mode of metal transfer across the arc affects weld soundness.

See C-Table 7.6 (12), (13), and C-7.12.1.3 or C-7.12.2.1(2) for discussion of current, polarity, and electrode extension. Electrode extension is not an essential variable. When WPSs are qualified under the provisions of 7.12.4, the Engineer should determine when changes in electrode extension appear to have changed welding conditions sufficiently to require proof of acceptable mechanical properties by requalification.

C-Table 7.6 (10) Voltage. The Contractor specifies the voltage in the WPS. Variations exceeding the specified limits necessitate requalification. In SAW, arc voltage can have a major effect on the chemical composition of the weld metal (see C-7.12.1.5).

With SMAW, arc length determines voltage. All SMAW performed under the provisions of the code uses low-hydrogen SMAW electrodes that require a very short arc length, commonly 1 mm to 2 mm [1/32 in to 1/16 in].

C-Table 7.6 (12) Travel Speed. Travel speed affects bead size, heat input, and weld cooling rates, especially important for fracture toughness control and for welding quenched and tempered steels. Proper selection of travel speed is also necessary to provide weld soundness and avoid incomplete fusion and slag entrapment.

Significant changes in travel speed change the solidification pattern in the weld pool. Welding using high travel speeds and high current, identified by long teardrop shaped weld puddles, can be undesirable because it causes lower melting point (weaker) constituents, if present in sufficient quantities in the base metal, to be pushed to the center of the weld where they may cause hot cracks. Qualification testing evaluates susceptibility to hot cracking, but this is also highly dependent on joint configuration.

SAW and EGW travel speeds are allowed a greater range of variation, compared to GMAW and FCAW, because with these processes, travel speed can often be substantially changed without interfering with the operation of the welding arc.

C-Table 7.6 (13) Heat Input. Large changes in heat input significantly change the mechanical properties of the weld and HAZ, and are not allowed without requalification. Excessively high welding heat input may significantly reduce weld metal and HAZ toughness, especially for heat treated steels. Lower welding heat input may increase the incidence of fusion discontinuities and affect soundness and mechanical properties, including decreasing toughness.

C-Table 7.6 (14–18) Multiple Electrode SAW. It is physically possible to perform SAW with multiple electrodes spaced far enough apart that the molten weld pool from a leading arc solidifies before the trailing arc or arcs reach the same point in the weld. To reliably achieve fusion under such conditions, the trailing arc would also have to be close enough to make the second weld before the slag on the first weld solidifies. When welding with a GMAW lead arc and a SAW trailing arc or arcs, the lead arc is allowed to feed a separate weld pool. GMAW produces minimal slag.

In SAW, the maximum spacing between lead and trail arcs that feed the same molten weld pool is about 20 mm [3/4 in]. The maximum spacing between multiple arcs in separate puddles is 75 mm [3 in].

C-Table 7.6 (19) Groove Area. Requalification is required if the number of weld passes changes by more than 25% for a given cross-sectional area of groove or fillet weld. This is to control changes in welding heat input. Because qualification and control of welding variables is based on welding heat input, it is unlikely that requalification will be necessary due to a change in the required number of passes. Production welding should reflect WPSs already qualified by test and the number of required weld passes should be about the same for the same volume of weld metal.

C-Table 7.6 (20–22) Groove Details. Any change in the joint preparation that may make welding more difficult, increase the likelihood of fusion discontinuities, or modify mechanical properties requires requalification.

C-Table 7.6 (24) Postweld Heat Treatment. At least two types of postweld heat treatment are possible. A stress relief heat treatment performed as described in 6.4 may significantly modify the metallurgical structure or mechanical properties of the weld or base metal. The weldment could also be annealed, normalized, or quenched and tempered, any of which would significantly alter the metallurgical structure and affect strength, ductility, and toughness. Normalizing and tempering heat treatments may improve or deteriorate toughness. Stress relief typically increases toughness and reduces strength.

Heat treatment of bridge weldments is rarely performed and is generally unnecessary. Properly designed and constructed bridge weldments have excellent fatigue life without heat treatment. Postheating at temperatures below 260 °C [500 °F] is done to remove hydrogen and is not considered PWHT. If the bridge member is to be heat treated to stress relieve the weld and HAZ, or is to be heat treated to improve its mechanical properties by recrystallization and transformation, the WPS qualification test plate(s) receive the same heat treatment before test specimens are removed by machining. Test specimens removed from heat treated welds are not to be reheated for any purpose.

C-Table 7.6 (25) Groove Welds in AASHTO M 270M/M 270 (A709/A709M) HPS 690W [HPS 100W] Steel. The plate thickness variation limitations applicable to these high strength, quenched and tempered steels provides closer control of welding heat because of concern over fusion discontinuities and cracking.

The limits on the thickness variation are based on the effect of thickness on cooling rate. Cooling rate is critical in quenched and tempered steels, significantly affecting the properties of the weld and HAZ. Rapid cooling can cause excessive hardness and increases the risk of hydrogen-induced cracking. Slow cooling may lower strength and toughness.

The HAZ of quenched and tempered steels of this strength level obtain their strength by transforming to martensite and bainite during the rapid cooling following each weld pass. To make the weld and HAZ ductile and tough, yet sufficiently strong, the bainite and martensite are limited by slower cooling rates at lower temperatures. However, if the HAZ remains hot for too long, the HAZ may become brittle from grain growth. If the welding heat input limits recommended by the manufacturer of the base metal are exceeded, strength and toughness of the weld and HAZ will be degraded. If the welding heat input used in combination with the preheat and interpass temperature is too low, low toughness and hydrogen-induced cracking may result.

C-Table 7.6 (26) Prior to the 2015 edition, WPS qualification required fillet weld soundness tests that consisted of the maximum single-pass and minimum multi-pass fillet welds that were to be made in production. These two fillet weld soundness tests qualified the WPSs for all production fillet welds. In the 2015 edition, this practice was replaced with a requirement to perform soundness tests on every nominal size used in production regardless of the number of passes used to deposit the weld. The number of passes to make a certain nominal fillet weld size is itself an essential variable.

C-Table 7.6 (27) Item 27 addresses the number of passes in the fillet weld since this is not covered by "maximum single-pass and minimum multi-pass" as in pre-2015 editions.

C-Table 7.6 (28) The dihedral angle is an essential variable since WPS adjustments may be necessary to achieve fusion to the root when the dihedral angle changes.

C-Figure 7.1. Early editions of the code, a specific joint geometry accompanied Figure 7.1, requiring the use of a root opening and included angle that was standard for only SAW welding. This yielded a variety of problems in qualification testing, particularly for out-of-position welding and gas-shielded semiautomatic processes. Figure 7.1 was changed to allow the use of alternate joint details that would be standard for the position of welding, and the welding process. Certain joint details were precluded because the combination of the root opening and the included angle for the specific thickness of test plate required precluded the extraction of an all-weld metal coupon from only weld metal.

C-Figure 7.2. See commentary for Figure 7.1.

C-8. Inspection

Part A
General Requirements

C-8.1 General

Prior to the 1980 edition of AWS D1.1, the *Structural Welding Code* stated, "The Inspector designated by the Engineer shall ascertain that all fabrication by welding is performed in conformance with the requirements of this code." This was often interpreted as giving the Owner ultimate responsibility for product quality, a position unacceptable to Owners. Subsequent revisions have clarified the separate responsibilities of the Contractor/fabricator/erector, as opposed to the Owner/Engineer, etc.

C-8.1.1 "For the purposes of this code" limits these definitions to inspection of bridge fabrication under this code. These provisions delegate responsibilities for inspection to the Contractor/ fabricator/ erector for assuring the quality of work performed is in conformance with the contract documents, and to the Owner for the accuracy of the contract documents and providing applicable guidance and oversight to the Contractor. This does not define the overall quality management program or prohibit Contractors from performing QA functions as a part of their quality program. In AWS D1.1, QC is termed fabrication/erection inspection and QA is termed verification inspection.

C-8.1.1.1 The Contractor's QC Inspectors and NDT personnel are responsible for conducting all inspections and tests prescribed by the contract documents, including applicable parts of this code, to ensure conformance of materials and workmanship. QC inspection and testing are a part of a quality management program.

C-8.1.1.2 QA is the prerogative, but not the responsibility, of the Engineer. The Engineer may provide independent QA inspection; enter into an agreement for the Contractor to provide independent QA inspection; or waive all QA inspection based on personal experience and the type or criticality of fabrication. When the Contractor arranges independent QA inspection services based on an agreement with the Engineer, it is important that this inspection be independent of the Contractor's QC inspection program, and also independent of those responsible for production. QA inspection verifies that the Contractor's fabrication methods and QC program produce the results required by the contract.

QA inspection may help to avoid errors and prevent delays, but its failure to discover a defect does not make the Engineer liable for the cost of repair or obligated to accept a deficient product. The Contractor remains responsible for the quality of the work, regardless of whether or not the Engineer has provided QA Inspection.

Inspection by the Engineer's representative should be done in a timely manner to avoid delays. Repetitive or delayed inspections by QA representatives may negatively affect project schedule and costs.

C-8.1.2 Inspector-Definition.

C-8.1.2.1 Inspectors performing QC duties for the Contractor may be employees of the Contractor or subcontracted representatives. Manufacturer's representatives may also provide expertise to evaluate special problems and recommend solutions to the Contractor.

C-8.1.2.2 The QA Inspector, when one is assigned, represents the Engineer. When there is more than one person performing QA inspection, the supervising Inspector represents the Engineer within the limits of authority that are established and reports all deficiencies in materials and workmanship to the Engineer and Contractor. In general, QA Inspectors should not be asked to comment on the structural adequacy of welded connections, materials substitutions, repair methods not covered by code, or other subjects that require an opinion relating to the design or performance of the structure. The Inspector's authority is generally limited to accepting materials and workmanship that conform to code requirements and rejecting those that do not. The Inspector does not hold the authority to modify the contract. Questions concerning the adequacy of proposals to repair defective weldments or to substitute materials should be directed to the Engineer.

C-8.1.3 Inspection Personnel Qualification.

C-8.1.3.1 Individuals assigned to perform inspection functions and make decisions about the acceptability of materials and workmanship need to be properly qualified. Certification of an Inspector based on successful completion of the AWS Qualification and Certification program, AWS QC1, is considered evidence of basic competence. A Senior Certified Welding Inspector (SCWI) satisfies the requirement for CWI. A Certified Associate Welding Inspector (CAWI), because he or she has less experience or has achieved an insufficient test score to pass the CWI or SCWI examination, does not satisfy the requirement of CWI.

Inspectors qualified by the Canadian Welding Bureau as described in 8.1.3.1(2) in conformance with the provisions of CSA W178.2 are considered the equivalent of an AWS Certified Welding Inspector.

Engineers and technicians who, on the basis of their education and experience are considered equal to an AWS CWI or CWB equivalent in their ability to perform inspection functions properly, may serve as Inspectors, with the Engineer's approval. This provision applies to both Contractor and Engineer representatives, and is intended to prevent highly qualified individuals from being barred from performing inspection functions solely because they are not certified by AWS or CWB. This code recognizes welding Inspector certification programs that are offered by AWS and CWB as being essentially equivalent. If other programs, public or private, are competently administered, reasonably specified, and open to the public, such certification programs may be considered equivalent to AWS and CWB programs.

C-8.1.3.2 An Inspector that was once certified under the provisions of 8.1.3.1(1) or 8.1.3.1(2), and has continued to perform acceptable welded structural steel inspection, may continue to perform inspection services under the provisions of this code. Whenever there is reason to question the competency or ability of an Inspector, or if documentation of ongoing work in inspection is inadequate, the provisions of 8.1.3.5 apply.

C-8.1.3.3 Assistant Inspector responsibilities might include checking joints during assembly prior to the start of welding, checking preheat and interpass temperatures, and inspecting fillet welds.

C-8.1.3.4 Personnel Qualification. The code requires NDT personnel be certified under a written practice developed in general conformance with ASNT *Recommended Practice No.* SNT-TC-1A, *Personnel Qualification and Certification in Nondestructive Testing*, or an equivalent program. Other programs may include the AWS NDE Certification Program and the ANSI/ASNT CP-189, ASNT *Standard for Qualification and Certification of Nondestructive Testing Personnel.*

An NDT Level I individual has the skills to perform specific calibrations, specific NDT, and with prior written approval of the NDT Level III, perform specific interpretations and evaluations for acceptance or rejection and document the results, while under the direct supervision of a Level II.

An NDT Level II individual has the skills and knowledge to set up and calibrate equipment, to conduct tests, and to interpret, evaluate, and document results in conformance with procedures approved by an NDT Level III. The Level II should be thoroughly familiar with the scope and limitations of the method to which certified, and should be capable of directing the work of NDT Level I personnel. The NDT Level II should be able to organize and report NDT results. The Level II should monitor and approve the results of Level I personnel on at least a daily basis. The Level II is responsible for providing guidance to the Level I and reviewing and signing all test reports generated by the Level I.

An ASNT NDT Level III individual has the skills and knowledge to establish techniques, interpret codes, standards and specifications, designate the particular technique to be used, and verify the accuracy of procedures. The individual should also have general familiarity with the other NDT methods. The NDT Level III is responsible for conducting or directing the training and examining of NDT personnel in the methods for which the NDT Level III will be qualified.

The Level III should have passed the basic and method examinations prescribed by SNT-TC-1A. The SNT-TC-1A tests required for Level III certification may be administered by ASNT or an independent third party deemed acceptable by the Engineer.

The code requires that NDT of non-FCM materials be performed by Level II technicians, or by Level I technicians only when working under the direct supervision of a Level II. Inspection by a Level III may not be recognized, as the Level III may not perform actual testing regularly enough to maintain the special skills required to set up or to conduct the tests, nor is a hands-on "practical" examination required for certification, unless certified under ASNT's ACCP testing. An ASNT Level III may conduct tests if that person has passed a practical examination and also holds a Level II certification. For Fracture Critical Members, under 12.16.1.2, testing of Fracture Critical Members should be done by either a certified Level II under the supervision of a qualified Level III, or by a Level III certified by ASNT and qualified as a Level II, unless the Engineer accepts other forms of qualification.

C-8.1.3.5 The Engineer should verify that Inspectors and NDT personnel are qualified. Whenever there is reason to suspect that QC individuals are not qualified, the QA Inspector should immediately notify the Contractor's representative and should withhold acceptance of affected work until proof of qualification has been provided and accepted. Proof of qualification may be in the form of testing, retesting, or certification.

C-8.1.3.6 Typical qualification as an NDT technician includes provisions for vision acuity testing on an annual basis and for color differentiation every three years.

C-8.1.3.7 Vision acuity testing is required at least every three years to verify that the Inspector can see properly. Testing every three years is not a guarantee that the Inspector's vision will continue to remain acceptable throughout the full three year period. If it appears that an Inspector is having difficulty seeing properly, a new vision acuity test by a qualified professional can be ordered. NDT technicians should be tested annually for visual acuity and every three years for color differentiation.

C-8.1.4 For most projects, Inspectors do not need the complete contract documents to perform the required inspections. Approved shop detail drawings, copies of contract plan sheets, and contract-related requirements for materials, assembly, and welding should be available.

C-8.1.5 Without prior notice of operations, Inspectors cannot properly prepare and perform the functions required by the code. The QA Inspector is encouraged to schedule activities to coincide with flow of work by the Contractor. Work done without advance notice to the QA Inspector, or when the QA Inspector has been denied access, may be rejected by the Engineer unless acceptable proof is presented that the work meets all requirements of the contract documents. Proper notice and access avoid delays and disagreements.

C-8.2 Inspection of Materials

To ensure that all materials conform to the requirements of the contract documents, the Contractor should review all material test reports and perform a detailed visual inspection of all received materials.

C-8.3 Inspection of WPS Qualification and Equipment

C-8.3.1 All welding performed in conformance with the provisions of this code is based on written WPSs. All WPSs, except those WPSs exempt from testing under the provisions of 1.3.7, 7.11, or 12.7, are based on the results of acceptable WPS qualification tests. Prior to the start of production welding the Inspector should verify that these requirements are met and verify that the welding personnel have access to the WPS that describes the welding to be performed.

C-8.3.2 The Inspector should determine that the welding and thermal cutting equipment to be used in the work is adequate for the intended welding or cutting operation, and is in proper working order. This inspection is to ensure that the equipment is capable of providing acceptable results when used by properly trained welding personnel. This includes visually examining the equipment, reading the identification and rating labels, and observing the equipment while being operated to ensure that it functions properly. Welding and thermal cutting equipment should not be allowed to be used in the work if its operation frequently malfunctions and creates weld or base metal discontinuities (see 6.28.1 for inspection frequency of equipment).

C-8.4 Inspection of Welder, Welding Operator, and Tack Welder Qualifications

C-8.4.1 See Clause 3, Terms and Definitions, for a description of the duties of welders, welding operators, and tack welders, and for the distinction between qualification and certification. Acceptance by the Engineer of proper evidence of previous qualification is encouraged to reduce the unnecessary duplication and expense of retesting.

C-8.4.2 Under the provisions of 7.21.4, a welder, welding operator, or tack welder's qualification may remain in effect indefinitely. Welding personnel may be tested and qualified in more difficult welding positions such as overhead or vertical, then use only easier positions such as flat and overhead for an extended period of time. The technique and skills needed for the rarely used, difficult positions may be temporarily lost or reduced. For these situations, requalification in the more difficult position to be used may be necessary to verify the required skill level.

Physical abilities and visual acuity generally decrease with the passage of time. Vision deficiencies may be compensated for by the use of corrective lenses. Loss of strength and manual dexterity may be compensated for by increased knowledge and skill. Some people may become temporarily unable to weld properly for any number of reasons.

Should less than acceptable welding skill be detected, the Inspector should take action as necessary to prevent unacceptable welding from being incorporated into the work. Welding personnel that appear less than fully qualified, or for any other reason are unable to properly perform the required welding tasks, should be prevented from continuing to weld until either requalified by test or provided other evidence of recovery from a temporary disabling condition.

C-8.4.3 Under 7.21.4, welding personnel qualification remains in effect indefinitely, provided the person retains their skills and has used the process within the past six months. Should the time period exceed six months, retesting is required but a 10 mm [3/8 in] plate test may be used to requalify for groove welds of all thicknesses. Subclause 12.8.1 of the FCP requires welding personnel to be qualified before welding on FCM, but also requalified annually. For these previously qualified welders and welding operators, requalification may be based on the results of radiographic testing of production welds in butt joints.

C-8.4.4 A QA Inspector may also observe the testing and sign as a witness.

C-8.5 Inspection of Work and Records

C-8.5.1 The Inspector inspects the structural steel for conformance to the contract documents regarding welding. The size, length, and location of all welds should be as specified. The surface of the structural steel should be visually inspected to verify that there have been no welds made that are not shown on the approved shop drawings or approved by the Engineer. Extra welds, particularly tack or temporary welds, may cause hydrogen-induced or fatigue cracking and should be avoided.

C-8.5.3 The electrodes, fluxes, and shielding gases are expected to be used as designed. Some electrodes are intended only for use with DC power sources operated electrode positive or electrode negative. Others are designed to be used with AC power sources. Some electrodes that may be used to weld in a given position or positions are not suitable for out-of-position welding. Other filler metals require a specific shielding gas mixture. Appropriate use of the welding materials with current AWS A5.XX specifications should be verified.

C-8.5.4 The Inspector should ensure that the welding conforms to the requirements of the contract documents performing by the necessary inspections. Materials should be inspected prior to assembly and during assembly. Preheat and interpass temperature control should be monitored. Welding is inspected while in progress and all completed welds and finished fabricated members are visually inspected. An Inspector need not watch each welder full time. Regular tours through active work areas provide the Inspector an opportunity to see each operation as it progresses and affords an opportunity to see how each welder is performing.

C-8.5.5 The Contractor and the various welding and inspection personnel need to know the status of weldments that have been completed and whether they have been inspected and accepted. Markings or inspection logs indicate those parts of the work that have been inspected and accepted and those needing repair. Such systems are also used to avoid needless reinspection. The provisions of this subclause are particularly appropriate for Inspectors that perform final inspection.

In many industries, the Inspectors are required to mark their acceptance or rejection directly on the welds or the adjacent steel. This is often an unacceptable procedure for bridges, particularly those erected in the bare unpainted condition. Any method of record keeping is acceptable, provided it is clear to the Contractor and approved by the Engineer. If die stamps are used, only low-stress type stamps should be used to mark acceptance or rejection in areas of bridge members subject to tensile stress, as other die stamp impressions may cause stress concentrations that could lead to fatigue cracking. Paint sticks or ink stamps may be used for die stamps where these marks will not be unsightly in the finished product.

C-8.5.6 Detailed records are required in an effective welding inspection program. They should be organized and kept as simple as possible. QC Inspectors keep records for the Contractor and QA Inspectors keep records for the Engineer. However, the QC inspection records should be available for review by the QA Inspector or Engineer upon request.

The use of “traveler forms” clipped to designated areas of each member and documenting all individuals (fitter, welder, Inspector, etc.) and actions (assembly, tacking, welding, layout marks, stiffener installation, splice drilling, etc.) is helpful to both QC and QA.

C-8.5.7 The Contractor is responsible for the quality of all NDT and necessary records of NDT results, unless otherwise specified.

C-8.6 Obligations of the Contractor

This subclause is only a partial listing of the Contractor's obligations. The Contractor is responsible for the quality of the work and ensures that it conforms to all requirements of the contract documents.

C-8.6.1 It is essential that QA personnel have safe access to all work and to necessary records. Cooperation between the Contractor's and Owner's personnel is essential.

C-8.6.2 The Contractor provides visual inspection and all NDT inspections required by the contract. Any materials and workmanship that do not conform to contract document requirements are to be corrected by the Contractor at the Contractor's expense. Routine methods of correction are described in 5.7. Some repair requires approval by the Engineer. Subclause 8.26 describes both the visual and NDT weld acceptance criteria.

C-8.6.3 The QA Inspector should routinely communicate directly with the QC Inspector or the representative designated by the Contractor. When a notice of rejection is necessary, it should be given to the QC Inspector or the responsible supervisor and confirmed in writing. The Engineer should be informed when a notice of rejection is issued.

C-8.6.4 Faulty welding and methods of weld removal can lead to base metal cracking because of hard HAZs. When base metal is stressed in the through-thickness, or "Z" direction, by repetitive defective welds and necessary repairs, lamellar tearing may occur. The Engineer should be notified of repetitive repairs. Replacement of base metal, or modifications to the design necessary to compensate for deficiencies created by material discontinuities, welding, or previous repairs are to be approved by the Engineer before beginning the corrective procedure.

C-8.6.5 When an Engineer orders NDT that was not specified in the contract documents, the Engineer subjects the Contractor to additional costs for preparing the weld surfaces for NDT and for performing or arranging for the required NDTs to be performed. There may also be costs associated with delays and costs for repairs that would not have been required if only visual inspection were specified. Except as provided, the Owner is responsible for the cost of extra work caused by NDTs that were not provided for in the contract documents.

C-8.6.6 The Contractor should attempt to schedule NDT so that the QA Inspector may monitor the testing as necessary. However, if the QA Inspector is available infrequently because of travel or other constraints, the Contractor should not be unreasonably constrained in completing the work. The QC and QA Inspectors, with Engineer's approval, should agree on a schedule and system for testing and acceptance.

C-8.7 Nondestructive Testing (NDT)

The NDT methods provided for in the code are radiographic testing, RT; ultrasonic testing, UT; magnetic particle testing, MT; and penetrant testing, PT. Only RT and UT have the capability of examining the full cross section of the weld. MT and PT are methods of inspection that enhance visual inspection of weld and base metal surfaces. MT may also reveal near-surface discontinuities. Each NDT method has advantages and disadvantages. Some methods of testing are expensive and require highly qualified technicians to perform the tests. Others are not expensive and do not require intensive operator training. RT has unique radiation safety considerations.

RT cannot be used effectively to examine corner and T-joints because restrictions on RT film placement prevent complete examination of these joints. UT is the preferred method for corner and T-joints.

C-8.7.1 Groove welds in main members receive examination using NDT methods. The only methods capable of inspecting the full weld cross section are RT and UT. The NDT method required is based on the type and loading of the joint. RT is the method selected for CJP groove welds in butt joints with tension or reversal of stress (alternating tension and compression) because of its sensitivity, accuracy, and nature of documentation. However, in corner and T-joints, RT is not reliable or cost-effective because of the configuration of the joint. UT is used for these joints because it has the capabilities of full-thickness evaluation. CJP groove welds loaded only in compression and/or shear do not have the same fatigue characteristics and failure would not have the same consequences compared to a CJP groove weld in a butt joint carrying tension. Therefore, NDT by either RT or UT may be used.

Both RT and UT are used to evaluate ESW and EGW; PAUT may be permitted per 8.7.8 to substitute for conventional UT of ESW. The large austenite grains that are common to the weld metal produced by these weld processes make UT sound transmission and evaluation more difficult. The grain boundaries may also deflect or reflect test signals. If there is lack of fusion, the unwelded portion of the joint may act as a smooth reflector 20° misaligned with the inspecting ultrasound, and cannot be accurately evaluated by amplitude methods. In addition to planar discontinuities, EGW may have gross spherical porosity, or piping porosity in the form of long tunnels, created in the solidifying weld metal by escaping gases. UT is not able to reliably detect or evaluate extensive porosity in these welds (see Table 8.5, Note 3). RT is used to supplement conventional UT in the evaluation of ESWs and EGWs. RT alone, however, may not detect planar discontinuities oriented parallel to the film or tight planar discontinuities, therefore the use of both RT and UT are complimentary.

C-8.7.2 Transverse butt joints in girder and beam webs, which carry shear stresses but are also subjected to tensile stress from bending, have different requirements from flange splices. The entire tension zone of the joint is not necessarily tested. Instead, only the portion of the joint subject to the most tensile stress, the 1/6 closest to the tension edge, is fully tested, and the remainder is treated as a shear joint. The design drawings and approved shop drawings should designate the tension flange area. If the joint is near a point of contraflexure, both flanges may experience applied tension, depending on loading conditions, in which case both are treated as "the tension flange" and 1/6 of the web depth from each flange would be tested by RT.

MT is best utilized as an aid to visual inspection. Every portion of every weld should be inspected visually when the weld is complete. Welds are also visually inspected between passes by the welder. When visual inspection is done properly and thoroughly, few if any discontinuities will be found by MT that are not visible to a skilled Inspector.

100% MT is required by the code for M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W] steel because this grade is more susceptible to hydrogen-induced cracking, justifying a more detailed inspection. The prod method of MT is not recommended for high strength steels because of the increased potential for arcing damage to the steel (see C-8.7.8).

C-8.7.5 Welds repaired based on rejection by NDT are reexamined after repair. The testing includes an area beyond the limit of the repair to ensure that the discontinuity has been replaced by sound weld metal and no additional defects occurred in the adjacent base metal or weld.

C-8.7.6 Subclause 5.7 lists general methods of repair. Weld repairs that are not routine, as described in 5.7, should be performed following an approved repair WPS.

C-8.7.8 Dry powder methods of MT are best for general steel fabrication. Tests can be performed without staining the steel with solutions, and testing will not interfere with the continuation of welding. Steel surfaces are to be clean and relatively smooth so tests can be accurately performed by either the prod or yoke method. When there are distinct lines in the surfaces or fusion boundaries of welds, such as weld toes or edges of mill scale, the iron powder indicating medium may become trapped in the surface depression, making it difficult to distinguish an indication of an unacceptable discontinuity from false indications caused by innocuous surface discontinuities acceptable under the code.

The prod method of MT requires large electrical currents to be conducted through the steel. The flow of current in the steel creates a magnetic field that will cause magnetic particles (iron powder) to outline discontinuities that interrupt the magnetic lines of flux. Magnetic lines of flux are normal to the flow of current in the prod method of MT. In the yoke method of MT, an electromagnet is used to generate the required magnetic field. Magnetic lines of flux flow along the surface and in the surface of parts being inspected directly between the poles of the electromagnet yoke, causing magnetic particles to outline discontinuities in the surface. Yoke equipment is generally more portable and less expensive.

Although the equipment orientation may vary, there is no difference between the MT indication produced by the prod or yoke methods. Both methods of inspection are based on the visual acceptance standards of 8.26. Adequate illumination of the tested area is critical to allow evaluation of particle patterns. The QC and QA Inspectors need to be satisfied with the methods and effectiveness of lighting, especially for congested or obstructed areas.

C-8.7.8.1

(1) Copper prods are not allowed on steels with a minimum specified yield strength of 345 MPa [50 ksi] or greater because these steels are more hardenable, and there is also a risk that copper melted by arcing of the prods can migrate into the steel along grain boundaries and cause cracking. Aluminum prods are specified to avoid the problems of copper, but still require careful use to avoid arcing. Aluminum prods build up a surface oxide that interferes with the necessary electrical contact, therefore frequent cleaning is necessary. Steel prods have been reported to provide good results with

reduced arcing, but rust needs to be periodically removed and the rounded ends maintained to ensure good contact at various angles of use.

(2) Arcing may be reduced by keeping the prods clean and by cleaning surfaces prior to testing. Best results are obtained when testing is performed on surfaces free of mill scale. High current is required for effective testing, but current demand may be reduced by smaller prod spacing. Arcing is reduced or eliminated when good electrical contact is established before the equipment is energized. Good prod pressure is essential to achieve good electrical contact.

C-8.7.8.2

(1) DC power is often specified because it has the ability to detect discontinuities that are slightly below the surface. However, many operators prefer AC power and consider it more effective for surface inspection.

(2) The lifting force that is specified is a measure of the effectiveness of the power of the magnet. When the lifting force is less than that specified, the inspecting magnetic field is proportionately weaker. When AC power is used, the lifting force is less, but the iron powder particles are more mobile due to the continuous 60 MHz change in polarity.

C-8.7.8.3 Surfaces are to be clean and dry so that there will be no interference with MT (iron powder) indicator mobility. The contact surface allows transmission of current in the prod method and magnetic lines of flux in the yoke method. Magnetic lines of flux can penetrate thin (1 mil to 2 mils) layers of nonconductive coatings such as paint, and this can be verified with the lift text in 8.7.8.2.

C-8.7.8.4 MT inspection is most sensitive to discontinuities that interrupt the magnetic lines of force. If the lines of force are parallel to the discontinuity, the discontinuity may be missed. Yoke or prod position and orientation during testing is critical. One of the more serious types of bridge fillet weld discontinuities is transverse cracking in longitudinal web-to-flange welds. These cracks may appear at regular intervals along the length of the weld. Sometimes called shrinkage cracks, these are best detected by placing the prods on the steel normal to the longitudinal axis of the weld. When using the yoke method, the yoke magnetic poles or feet are placed as close to the weld as possible, almost directly on the weld, parallel to the longitudinal axis. The yoke feet are usually too large to allow the yoke to be placed directly on the weld without first making edge contact with the web and flange. The yoke needs good areas of contact to be effective.

Welds are examined in a manner that will reveal all significant discontinuities. Complete MT requires overlapping test positions with the test equipment oriented both parallel and transverse to the axis of the member at each test site. Discontinuities are best detected when their axis is normal to the magnetic lines of force. Therefore, the prod technique is most sensitive to discontinuities whose major axis is parallel to a line drawn between the two prods, whereas the yoke technique is most sensitive to discontinuities whose major access is normal to a line drawn between the two poles.

C-8.7.8.5 Thorough reporting of test conditions and results provides proper documentation that welds have been properly tested and meet contract requirements.

C-8.7.9 PT may be used under some conditions. It is a simple test method and is inexpensive for localized tests of smooth surfaces. When more extensive testing is required, PT may become more expensive than MT because of long dwell times, surface preparation, testing materials cost, and cleanup requirements. It requires clean, smooth surfaces to produce accurate test results.

There is no general requirement for PT in the code. This method of inspection may be used to aid visual inspection, and to detect and define the extent of discontinuities open to the surface. The size of the indication is not indicative of discontinuity size. The size of discontinuities discovered by PT should be determined by visual inspection aided by careful excavation, if necessary, after the inspecting medium has been removed.

C-8.7.10 When used in accordance with Annex J, PAUT is an effective test method with noted advantages, including many of the limitations of conventional UT:

(1) Sweeping through multiple angles, as required by Annex J, results in the improved detection of defects such as porosity and slag over conventional UT

(2) Encoding the scan allows for informative imaging and a permanent (electronic) record; and

(3) The combination of encoding and swept angles operated to a defined scanning plan results in repeatability and makes it unlikely that an operator will miss a discontinuity.

PAUT, in accordance with Annex J, may be substituted for RT when approved by the Engineer. Compared to RT, UT offers improved evaluation for planar discontinuities, like cracks; PAUT improves this evaluation and also provides a permanent record.

Just as conventional UT and RT have different detection capabilities (each may find discontinuities the other will not), the RT and PAUT methods in Part B and Annex J have different detection capabilities; however, both are expected to yield similar reliability in inspected product.

As of 2015, PAUT had been adopted by other industries as an alternative to either UT or RT. It is permitted as an alternative UT technique in ASME B31.3 Code Case 181; ASME B31.3 permits UT as an alternative to RT. PAUT and other advanced UT techniques are permitted in lieu of RT of pressure vessels by ASME Boiler and Pressure Vessel Code Case 2235-9, and in lieu of RT of tanks by API 650. Preliminary research by both FHWA and the Florida Department of Transportation indicates that application of PAUT for bridge welds should result in acceptance rates similar to current AWS D1.5 inspection requirements.

Part B
Radiographic Testing (RT) of Groove Welds in Butt Joints

C-8.9 General

C-8.9.1 The procedures and standards set forth in this subclause are primarily designed for the RT inspection of CJP groove welds in butt joints in bridges. Typical geometries for structural connections and design requirements for these structures were considered. An effort was made to incorporate ASTM standards and utilize the procedures of the ASME *Boiler and Pressure Vessel Code* whenever possible.

C-8.9.2 Because this subclause does not address RT of all possible configurations of welds and joints in bridge structures, variations are allowed with the agreement of the Contractor and Engineer. Variations are also allowed for proven innovations in RT technology that have not yet been adopted into the code.

C-8.10 RT Procedure

C-8.10.1 Procedure. The single source of inspecting radiation is specified to avoid confusion or blurring of the RT image. Subclause 8.10.5 contains limits on the size and placement of the source to limit geometric unsharpness. RT sensitivity and sharpness is judged solely on the quality of the image quality indicator (IQI) image(s). For more detailed information see ASTM E747.

C-8.10.1.1 Digital Radiography. Direct radiography (DR) using a DDA and computed radiography (CR) are distinct techniques, each governed by a different ASTM standard.

C-8.10.2 Ionizing radiation and chemicals used in RT may present serious health hazards, so safety regulations need to be rigorously followed.

C-8.10.3 Removal of Reinforcement. If the Engineer desires finishing of weld surfaces not otherwise required to be flush or otherwise smoothed (see 5.6) before RT, this should be in the contract documents. The Engineer and the Contractor should agree in advance on which weld surface irregularities need not be finished or otherwise modified, unless surface irregularities interfere with the interpretation of the radiograph. When reviewing radiographs in the absence of information describing the weld surface, distinguishing internal discontinuities from surface irregularities is sometimes not possible.

C-8.10.3.1 Weld tabs are removed prior to RT inspection so that the radiograph will examine the welds as finished and placed in service. Contraction cracks, difficult to identify in a radiograph, may occur in the weld at the interface between weld tabs and the edge of the plate or shape joined by the weld. For certain welds or joints, such as when plate edges will be subsequently removed during cutting of web camber or multiple flanges, the Engineer may waive the requirement to remove weld tabs.

C-8.10.3.2 Steel backing is removed when required by 5.13.3, or may remain in place when allowed by 5.13.3 or 5.13.3.1 When removed, the remaining weld surface and adjacent steel affected by the removal are finished flush (see C-5.6.2.1). Tack welds between backing remaining in place and base metal are subject to the requirements of the applicable provisions of 5.3.7.

RT is performed following any required removal of backing so that the radiograph will examine the welds as finished and placed in service.

C-8.10.3.3 When weld reinforcement and/or backing is not removed, shims placed under the image quality indicators (IQIs) are used so that the IQI image may be evaluated on the average total thickness of steel (weld metal, backing, reinforcement) exposed to the inspecting radiation.

C-8.10.4 Radiographic Film. The provisions of this subclause are to provide fine grain film and to avoid coarseness in the image that may result from the use of fluorescent screens.

C-8.10.5 Technique. To avoid as much geometric distortion as possible, the source of radiation is centered with respect to the portion of the weld being examined.

C-8.10.5.1 Geometric Unsharpness. This subclause is provided to limit geometric unsharpness, which causes distortion and blurring of the RT image.

C-8.10.5.2 Source-to-Subject Distance and C-8.10.5.3 Source-to-Subject Distance Imitations. These subclauses are intended to limit geometric distortion of the object as shown in the radiograph.

C-8.10.6 Sources. This subclause provides that X-ray units, 600 kvp maximum, and iridium 192 sources may be used for all RT, provided these have adequate penetrating ability and can produce acceptable radiographic sensitivity based on IQI image as provided in 8.10.7. Since cobalt 60 produces poor RT contrast in materials of limited thickness, it is not approved as a RT source when the thickness of steel being radiographed is 75 mm [3 in] or less. When the thickness of steel being radiographed exceeds 75 mm [3 in], cobalt 60 is often preferred for its penetrating ability.

Care should be taken to ensure that the effective size of the radiograph source is small enough to preclude excessive geometric unsharpness. Geometric unsharpness is defined as the fuzziness or lack of definition in a radiographic image resulting from the source size, object-to-film distance, and source-to-object distance. Geometric unsharpness may be expressed mathematically as:

$$U_g - \frac{F(L_i - L_o)}{L_o}$$

where U_g is the geometric unsharpness, F is the size of the focal spot or gamma radiation, L_i is the source-to-film distance, and L_o is the source-to-object distance.

C-8.10.7 IQI Selection and Placement. Since RT sensitivity and the acceptability of radiographs is judged using the image of the required IQIs, care is taken in describing the manufacture and use of the required IQIs. IQIs are placed near the extremities of weld joints where geometric distortion will contribute to lack of sensitivity in the radiograph.

C-8.10.7.1 IQIs may be placed only on the source side unless otherwise approved by the Engineer. Failure to place the IQIs on the source side during the RT exposure, without prior approval of the Engineer, is cause for rejection of the radiographs.

C-8.10.7.2 The IQI thickness is to be as specified. An IQI with a smaller essential hole or thinner wire size may be used at the Contractor's option. These IQIs require greater sensitivity.

C-8.10.7.3 The IQI selected using Tables 8.2A or 8.2B is based on either thickness T1 or T2.

C-8.10.7.4 Figure 8.1E provides general dimensional information for hole-type IQIs. ASTM E1025 governs the manufacture of hole-type IQIs.

C-8.10.7.5 Figure 8.1F provides general dimensional information for wire IQIs. ASTM E747 governs the manufacture of wire IQIs.

C-8.10.8 Technique. Welds are radiographed and the film indexed by methods that will ensure complete, continuous inspection of the weld within the limits specified. Flange-to-flange welded butt joints that join segments of thick flanges in beams and girders are particularly difficult to radiograph because of geometric distortion and undercut from scattered radiation at the ends of the weld that represent the flange edges. Weld discontinuities at these critical locations are limited under the provisions of 8.26.2. Centering of the source close to the flange edge will avoid geometric distortion at the edge of plate. The use of "edge blocks" will help to allow RT evaluation of the edge, since all radiation will still pass through solid metal within the area of interest.

C-8.10.8.2 Overlapping Images. Because of dimensional limits and distortion, it may be necessary to make multiple exposures to examine longer welds. Several films of standard lengths to radiograph longer welds may also be used when a single source exposure is taken, provided IQIs on each film indicate acceptable image sharpness is maintained. Longer welds may also be radiographed with multiple exposures and several films.

C-8.10.8.3 Backscatter. Backscattered radiation can cause general fogging and produce artifacts in the radiograph. The method described in this subclause will identify backscattered radiation so that corrective steps can be taken.

C-8.10.9 Film, SPIP, and DDA Width. RT is designed to inspect all of the weld zone. Film widths need to be sufficient to inspect all portions of the weld joint and have sufficient room for weld identification.

C-8.10.10 Quality of Radiographic Film and Digital Images. Standard imaging plates, as in any radiography, may be masked using lead shielding. Masking may be necessary to eliminate internal and backscatter radiation. In digital radiography, backscatter and unnecessary exposure may also contribute to the deterioration of the panel. Particularly, scattered radiation that may strike the digital detector array crystals horizontally may cause more rapid deterioration.

Histogram normalization "smooths" the small integral steps of the digital image. This is similar to taking the noise out of a digital image. Gamma correction is normalization of the various shades of gray. All normalized images are saved as separate files from the original raw image. If there is any concern regarding the integrity of the image after normalization enhancements, the viewer can refer to the raw image, which cannot be overwritten.

Sub-images are useful for facilitating inspection, such as when non-deleterious aberrations occur. For example, an Inspector may verify that indications that appear to be scratches are the result of grinding and, the Inspector can note this on a sub-image, thereby documenting this evaluation without modifying the original image.

C-8.10.11 Density, Brightness, and Contrast Limitations. To avoid the necessity of making multiple exposure or using films of more than one exposure speed, radiographic films within the full limits of useful film density may be used. In general, within the limits of density approved by the code, the greater the film density, the greater the radiographic sensitivity.

C-8.10.11.1(1) H & D Density. The calculation method for determining the film density is given. Light intensity is measured in conformance with the methods in ASTM E1742.

C-8.10.11.1(2) Digital Image Sensitivity Range. The weld transitions in thickness provided for this subclause are expected to be gradual with a maximum slope of 1:2.5 as shown in Figure 4.7. For large transitions, the film density should be established for the thinner material. The film density for the thicker material is allowed to be below that required in 8.10.11.1, unless otherwise required.

C-8.10.11.2 Digital Image Sensitivity Range. Radiographic film transmitted density measures the amount of light that passes through the film; however, this is not applicable to digital radiography. In digital images, light balance in the image is controlled through the brightness and contrast settings.

C-8.10.12 Identification Marks. Information needs to uniquely identify the radiograph and match the radiograph to the weld joint. Radiograph identification marks and location identification marks are used to locate discontinuities requiring repair, allow repairs to be made without repetitive or unnecessarily large excavations, and to verify that discontinuities have been repaired as demonstrated by the subsequent repair radiograph. Permanent indications on the steel such as punch-marks, numbers, and letters should be minimized, limited to those needed to locate the film's position. All such marks should be made with low-stress or mini-stress stamps.

The information provided on the radiograph ensures traceability and control of the RT.

C-8.10.13 Linear Reference Comparators. Hole-type IQIs may be used as a linear reference comparator in digital radiography, using the cursor measuring tool built into the software. Wire-type IQIs are typically not used as comparators because the wires are relatively thin and the ends may be hard to locate, making measurement difficult.

C-8.10.14 Edge Blocks. Flange-to-flange welded butt joints that join segments of thick flanges in beams and girders are particularly difficult to radiograph due to geometric distortion and undercut from scattered radiation at the ends of the weld that represent the flange edges. Weld discontinuities at these critical locations are limited under the provisions of code.

On weldments over 12 mm [1/2 in] in thickness, it was demonstrated by using drilled holes and lead indicators near the top edge of a weldment that a substantial portion of this edge was over exposed and could not be shown, leaving left the possibility of not showing discontinuities. By using edge blocks and a standard source alignment, lead indicators and drilled holes could be shown on a radiograph at the plate edge.

C-8.11 Acceptability of Welds

The provisions of 8.26.2 prescribe the quality of welds radiographed for bridge structures.

C-8.12 Examination, Report, and Disposition of Radiographs

C-8.12.1.1 Film Radiography. A suitable variable intensity illuminator with spot review or masked spot review capability is required for more accurate film viewing with the viewers' eyes shielded from the portions not under examination. The ability to adjust the light intensity reduces eye discomfort and enhances the visibility of film discontinuities. Subdued light in the viewing area allows the reviewer's eyes to adjust so that small discontinuities in the radiographic image can be seen. Film review in complete darkness is not advisable because the contrast between darkness and the intense light from portions of the radiograph with low density cause discomfort and loss of accuracy. The viewer should properly illuminate radiographs with densities up to the maximum allowed film density of 4.0.

C-8.12.3 Radiographic Film or Digital Image Retention. The term "a full set of radiographs" means one radiograph of acceptable quality from each radiographic exposure required for complete radiographic inspection, including radiographs showing discontinuities that were subsequently repaired and re-radiographed. If the Contractor elects to load more than one film in each cassette to produce an extra radiograph for the Contractor's own use, or to avoid possible delays caused by film artifacts or false indications, or both, the extra radiographs, unless otherwise specified, are the property of the Contractor.

Part C
Ultrasonic Testing (UT) of Groove Welds

C-8.13 General

C-8.13.1 The ultrasonic testing (UT) provisions are a direct method for testing weldments, designed to ensure reproducibility of test results when examining specific reflectors. Most CJP groove welds within the range of the thickness given may be satisfactorily tested using the provisions of Clause 8, Part C.

C-8.13.2 Variations to standard UT procedures as described in this code are allowed with the approval of the Engineer. Such variations may be needed because of unusual joint geometries, thicknesses less than 8 mm [5/16 in] or more than 200 mm [8 in], other unusual applications, or the use of new or innovative techniques or equipment.

During routine fabrication of structural steel, all welds should be inspected and accepted by QC prior to being coated. Where coated surfaces are to be tested, the condition of the test surface should be considered before routine testing is done, including measurement and reporting. Although the code prohibits routine UT through coatings, a good, tight, uniform coating may not interfere with the application of UT. The Engineer's approval is required for UT through any coating. Calibration of transducers and UT systems on similarly coated specimens may help identify attenuation or other factors caused by the coating.

C-8.13.3 The code requires that RT be used as a supplement to UT when examining ESW and EGW welds because of the inability of UT to accurately evaluate porosity on an amplitude basis. Piping porosity in this type of weld, although appearing cylindrical, usually has a series of cascaded surfaces throughout its length. The UT reflectivity of these cascaded surfaces does not generally correspond to a straight line reflector such as that expected from a side-drilled hole, itself a difficult discontinuity to quantify.

Piping porosity often responds to UT like a series of single point reflectors, as if received from a line of spherical reflectors. This results in a low amplitude-response reflecting surface, resulting in a trace that has no reliable relationship to diameter and length of this particular type of discontinuity.

In addition to this problem, the general nature of piping porosity in conventional ESW and EGW welds is usually such that holes in the central portion of the weld may be masked by other surrounding holes. The branches or tunnels of piping porosity have a tendency to tail out toward the edges of the weld nugget. UT can only effectively evaluate the first major reflector intercepted by the sound path (see Table 8.4, Note 5, Table 8.5, Note 3). No mention of additional RT is presently made with reference to testing EGW welds in Table 8.4, as this process is not allowed for tension welds.

C-8.13.4 The provisions of Clause 8, Part C have been developed for the testing of welded joints. Base metal testing should be as described in AASHTO M 270M/M 270 (ASTM A709/A709M).

Base metal cracks and other discontinuities discovered by UT are included in the report to the Engineer.

C-8.14 Extent of Testing

C-8.14.1 The required amount of testing to be performed is as described in 8.7.

C-8.14.2 Proper UT inspection requires knowledge of the joint and base metal configuration and the welding process used. Based on this information, the orientation, location, and nature of probable discontinuities can be established. The testing angles described in Table 8.3 are based on the thickness and joint configuration, with special requirements for welds made by EGW or ESW.

C-8.15 UT Equipment

Standards are established for UT discontinuity detectors to ensure adequate mechanical and electrical performance when used in conformance with the requirements of the code.

Subclauses 8.15.1 and 8.15.5 cover the specific equipment features considered for equipment qualification. Subclauses 8.15.6 through 8.15.7 cover the dimensional and performance requirements for transducers.

C-8.15.7.2 Transducer size and shape is limited to reduce the scatter in the results of discontinuity evaluation, thought to be attributed to transducer size. Round transducers are not acceptable for angle-beam testing.

C-8.16 Reference Standards

C-8.16.1 Reference blocks are used for the calibration and certification of equipment.

C-8.16.2 The code prohibits the use of square corners for calibration purposes because of the inability of acquiring amplitude standardization from various corners that are called "square." Factors that may affect amplitude standardization are: the size of the fillet or chamfer on the corner, if any; the amount the corner is out of square (variation from 90°); and surface finish of the material. When a 60° probe is used, it is very difficult to identify the indication from the corner due to high amplitude wave mode conversions occurring at the corner.

C-8.17 Equipment Qualification

C-8.17.1 The use of ASTM E317 for horizontal linearity qualification has been eliminated and a step-by-step procedure outlined in 8.22.1 is used for certification.

C-8.17.2 The vertical linearity of the UT unit is calibrated at intervals not exceeding two months by the procedure described in 8.22.2 to verify continued accuracy. Certification is maintained with use of information tabulated on a form similar to Annex E, Form E-1 (example information is also shown).

Caution is to be used in the application of alternate methods for vertical linearity certification. Normal ways of translating voltage ratios to dB graduations generally cannot be used due to potentiometer loading and capacitance problems created by the high frequency current transfer. A high degree of shielding will also be maintained in all wiring.

C-8.17.3 Internal reflections may provide false indications of discontinuities or distort the indication rating of reflected sound. Transducers are checked after 40 hours of use.

C-8.17.4 Because the contact surfaces of search units wear and cause loss of discontinuity location accuracy, the code requires accuracy checks of the search unit after a maximum of eight hours use. The responsibility for checking the accuracy of the search unit after this time interval is placed on the individual Level II performing the work.

C-8.18 Calibration for Testing

C-8.18.4.1 Indications of at least two plate thicknesses is to be displayed in order to ensure proper distance calibration, because the initial pulse location may be incorrect due to a time delay between the transducer crystal face and the search unit face.

C-8.18.5.1 The horizontal location of all screen indications is based on the locations at which the left side of the trace deflection breaks the horizontal base line. The initial pulse location will always be off to the left of the zero point on the display. Care is to be taken to ensure that the pulse at the left side of the screen is the initial pulse and not one from a reference reflector. Verify by removing search unit from workpiece.

C-8.19 Testing Procedures

C-8.19.1 The material needs to be marked in a suitable manner to allow for measurement, calculation, and recording of discontinuities.

C-8.19.3 The surfaces on which the transducer is placed are to be free of any materials that will interrupt, disturb, or distort the transmission of sound. Weld spatter, dirt, and loose mill scale will prohibit free scanning movement and the intimate contact of transducer and steel, with resultant loss of sound transmission and reception. Grease, oil, and coatings, in addition to possible loss of contact, may distort the directionality of the sound path and weaken both sound transmission and reception (see 8.13.2 for testing through coatings and the use of nonlisted couplants).

C-8.19.4 It is recognized that couplants other than those specifically allowed in the code may work equally well or better for some applications. It is beyond the scope of the code to list all fluids and greases that could be acceptable couplant materials. Any couplant material, other than those described in the code, that has demonstrated its capability of performing to code requirements, may be used in inspection on agreement between the Engineer and the UT Inspector (see 8.13.2).

Tests should be conducted to quantify variations in the response from the reference reflector caused by differences between the couplants used for calibration and for actual testing. Glycerine will give different values than cellulose gum. Any measurable difference should be taken into account in discontinuity evaluation.

C-8.19.5 The provision to search the base metal for laminar reflectors is not intended as a check of the acceptability of the base metal, but rather to determine the ability of the base metal to accept specified UT procedures (see 8.13.4).

C-8.19.5.1 A procedure for size evaluation of laminar and lamellar discontinuities is provided in 8.23.1.

C-8.19.5.2 Grinding the weld surface or surfaces flush may be necessary to obtain geometric accessibility for alternate UT procedures when laminar discontinuities in the base metal prohibit testing using standard procedures. Contract documents may require flush grinding of tension groove welds to improve fatigue performance and to facilitate more accurate RT and UT.

C-8.19.6 When required by Tables 8.4 and 8.5 as applicable, the sensitivity for evaluation of discontinuities is increased by at least four decibels above the maximum sensitivity required to produce reference level amplitudes from a discontinuity of maximum size (reflection amplitude) if detected at the maximum testing sound path. This increased sensitivity assures that defects are not missed as a result of planar-type discontinuities at the fusion boundary.

C-8.19.6.1 UT under the code is performed following specific procedures to provide standard results and repeatability between UT technicians. The UT technician does not normally deviate from the given procedures without approval by the Engineer. The procedures as provided are integral with the specified transducers and the acceptance criteria of Tables 8.4 and 8.5. A change in procedure or transducer necessitates a change in the acceptance criteria of Tables 8.4 and 8.5. Use of other angles or weld faces may result in a more or less critical examination than established by the code.

Table 8.3 was established on the basis of a search unit angle of 70°. This angle will best detect and more accurately evaluate discontinuities having a major dimension oriented normal or near normal to the combined residual and applied tensile stresses, considered most detrimental to weld integrity. Conservatively assuming that all discontinuities could be oriented in this direction, the 70° probe should be used whenever possible. For optimum results, a 250 mm [10 in] sound path distance has been established as maximum for standard testing. However, there may be some joint sizes and configurations that require longer sound paths to inspect the weld completely.

Testing procedures 6, 8, 9, 12, 14, and 15 in the procedure legend of Table 8.3, identified by the top quarter designation GA or the bottom quarter designation GB, require evaluation of discontinuities directly beneath the search unit, necessitating a flat contact surface. More accurate results may be obtained by testing these large welds from both Face A and Face B.

The procedure chart was developed considering the above factors. Note 5 of Table 8.3 provides that discontinuities in tension welds in bridges are not evaluated directly beneath the search unit, but by passing sound directed from the opposite side of the joint.

The pitch-and-catch technique for UT evaluation of incomplete fusion in ESW and EGW joints is intended as a secondary test of the area along the original groove face in the middle half of the plate thickness. This test may be specified to further evaluate an UT indication in this area that appears on the display at scanning level but is not rejectable by indication rating. The expected pitch-catch amplitude response from such a reflector is very high, making it unnecessary to use the applicable amplitude acceptance levels. However, since no alternative is provided, these decibel ratings are used. As only a specific location is being evaluated, predetermined positioning of the probe can be made. Probe-holding fixtures are most helpful in this operation.

The use of the 70° probe in the primary application is adequate in testing ESW and EGW fusion surfaces of material 65 mm [2-5/8 in] and less in thickness because acceptance levels are such that proper evaluation can be expected.

Legend "P." Because of the high energy loss that is possible due to wave mode conversion, the use of 60° probes is prohibited for evaluation when using the pitch-and-catch method of testing.

C-8.19.6.2 Access for butt joints is provided from both sides, whereas T- and corner joints may have limited access. Because the nature of butt joints is often critical to overall structural performance, butt joint quality is verified by examination from both sides of the joint. Although discontinuity characteristics and orientation are routinely assumed for a given joint design, UT of the entire weld using intersecting sound paths is required, whenever possible, to detect any discontinuities that may be present in locations or orientations other than those assumed.

C-8.19.6.3 The procedure provided is to ensure evaluation of all discontinuities that may appear on the display.

C-8.19.6.4 The attenuation rate of two decibels per 25 mm [1 in] of sound travel, excluding the first 25 mm [1 in], is established to provide for the attenuation (absorption) of sound energy in the test material. The sound path distance used is the dimension on the display. The rounding of numbers to the nearest decibel is accomplished by maintaining the fractional or decimal values throughout the calculation, and at the final step, advancing to the nearest whole decibel value when values of one-half decibel or more are calculated, or by dropping the part of the decibel less than one-half.

C-8.19.6.5 Gain is the adjustment to increase instrument sensitivity. Attenuation is the downward adjustment of instrument sensitivity. The type of instrument adjustment system used affects the method for calculating the indication rating.

C-8.19.7 The required six decibel drop in sound energy may be determined by adding six decibels of gain to the indication level with the calibrated gain control, then rescanning the weld area until the amplitude of the discontinuity indication drops back to the reference line.

When evaluating the length of a discontinuity that does not have equal reflectivity over its full length, its length evaluation may be misinterpreted. When a six decibel variation in amplitude is obtained by probe movement, and the indication rating is greater than that of a minor reflector, the operator should record each portion of the discontinuity that varies by ±6 dB as a separate discontinuity to determine whether it is acceptable under the code based on length, location, and spacing.

C-8.19.8 In the procedures specified for UT testing, the zero reference level for discontinuity evaluation is to be the reference level established during calibration for an indication reflected from a 1.5 mm [1/16 in] diameter hole in the IIW ultrasonic reference block. When actual testing of welds is performed, the minimum acceptable levels are given in decibels for various weld thicknesses. The minimum acceptance level is provided in Table 8.4 or Table 8.5, as applicable. In general, the higher the indication rating or acceptance level, the smaller the cross-sectional area of the discontinuity normal to the applied stress in the weld.

Indication ratings up to 6 dB more sensitive than rejectable need to be recorded on the test report for welds designated as being "Fracture Critical" so that future testing, if performed, may determine if there is discontinuity growth. The UT acceptance criteria are identical for welds in fracture critical regions and nonfracture critical welds.

C-8.19.9 Welds containing defects should be physically marked directly on or adjacent to the weld to identify the location and extent of the defect. The depth of the defect is noted nearby on the steel. This enables the repair to be performed at the location of the defect, rather than excavating an entire region attempting to find the defect. Welding personnel may not be able to interpret the UT technician's report to determine the location and nature of the defect.

C-8.19.9.1 Following repair, the results of the test of the repaired region are placed on the previous report form, with the designator "R1" added to indicate that a repair has been made. Subsequent repairs to the same discontinuity within the joint would receive a designation such as R2, R3, and so forth. Use of the same form for the original weld and all repairs improves control of the documentation of the testing, as well as provides records of unrepaired regions that may be subsequently inspected following repairs in adjacent areas.

C-8.19.9.2 Welds containing a large number of recordable indications, with subsequent repairs, may fill an existing UT report form. Additional new forms, tied directly to the previous report through a numbering system, may be used.

C-8.19.10 Welds rejected using the UT criteria of Tables 8.4 or 8.5, as applicable, may be repaired using the methods described in 5.7, unless replacement is selected by the Contractor in conformance with 5.7.2. The repaired or replaced weld should be inspected using the same criteria as the previous weld, reported on the same report form or on an additional report form in conformance with 8.19.9.

C-8.20 Preparation and Disposition of Reports

C-8.20.1 All welds subjected to UT should have a report showing the results. For welds that are acceptable without repair, testing information is not required regarding any acceptable indications. The report for an acceptable weld need only provide the weld identification, a statement of acceptance, and the Inspector's signature.

C-8.20.3 The term "a full set of completed report forms" means one report for each weld inspected by UT, whether the weld was accepted, rejected and repaired, or replaced. Should entire assemblies be replaced, submittal of UT reports for the piece replaced need not be submitted. The Contractor need not retain copies of the forms once the full set is provided to the Owner, nor retain copies after one year following completion of the project should the Owner waive the requirement for submittal of the UT reports. The Contractor should not discard reports until the Owner has acknowledged receipt of written notice regarding planned UT report disposal.

C-8.21 Calibration of the UT Unit with IIW or Other Approved Reference Blocks

The procedure for the calibration of the UT search units using calibration blocks is provided in this subclause. The reference standards for the calibration blocks are provided in 8.16. The frequency of testing of search units is described in 8.17.3 and 8.17.4.

C-8.22 Equipment Qualification Procedures

The procedures for the qualification of the UT equipment is provided in this subclause. It is performed using a standard straight beam search unit meeting the requirements of 8.15.6 on IIW or DS calibration blocks as referenced in 8.16. The frequency of equipment calibration is described in 8.17. Since this qualification procedure is performed with a straight beam search unit that produces longitudinal wave with a sound velocity of almost double that of shear wave, it is necessary to double the shear wave distance ranges to be used in applying this procedure. Example: The use of a 250 mm [10 in] screen calibration in shear wave would require a 500 mm [20 in] screen calibration for this qualification procedure.

C-8.23 Discontinuity Size Evaluation Procedures

C-8.23.1 Straight (Longitudinal) Beam Testing. The technique described provides a consistent method for determining the location and length of both large and small discontinuities when using a straight beam transducer.

C-8.23.2 Angle-Beam (Shear) Testing. When using angle-beam testing to determine acceptance of welds using Tables 8.4 or 8.5, the length of the discontinuity is measured if the reflection exceeds the limits of a Class D discontinuity, which is acceptable regardless of length. The technique described provides a consistent method for determining the location and length of discontinuities when using an angle-beam transducer.

C-8.24 Scanning Patterns

The use of the scanning patterns of this subclause provide standardized approaches to evaluate the full thickness and width of the weld, with patterns applied from both sides of the joint when possible to produce sound from crossing directions. The use of a particular scanning pattern for a particular weld is not described by code, rather, the scanning pattern should be selected by the UT technician based on the orientation of the anticipated discontinuity.

For ESW and EGW welds, see Legend "P" in Table 8.3.

C-8.25 Examples of dB Accuracy Certification

The decibel dB accuracy procedure as described in 8.22.2 is complex. The use of the example in Annex E, Part B is available to assist the user of the code in the application of this procedure.

Part D
Weld Acceptance Criteria

C-8.26 Quality of Welds

C-8.26.1 Visual Inspection. All welds are required to be visually inspected. Visual inspection is performed before welding, during welding, and after welding, as necessary to ensure that the requirements of the contract documents are met and that all welds conform to the visual requirements of this subclause. The Inspector is not required to inspect each weld pass, but periodically observe welding with sufficient frequency to verify the skills of the welder, proper joint preparation, WPS variables, and the visual quality of typical root, intermediate, and final weld passes. In addition to inspection before and during welding, the Inspector is expected to visually inspect every completed weld to verify conformance to these requirements (see C-8.5).

Each welder, welding operator, and tack welder should be a visual Inspector of his or her own work. Welding personnel should know when welds display visual discontinuities not acceptable under the code. Because each weld pass of every weld is to be inspected by the welder, and the Inspector monitors welding in progress and makes a detailed inspection of completed welds, major weld defects or gross nonconformance to the code should be detected.

Welds are considered to be visually acceptable if they comply with the requirements of this section. Because it may not be remedied by a subsequent pass, any crack or other significant defect in any weld pass makes the weld unacceptable and requires repair or replacement of the weld. Such defects can often be seen by the welder or Inspector. If the initial weld pass or any subsequent weld pass is visually unacceptable, the welder should not continue to weld and cover the defect with the deposition of additional weld metal.

Small discontinuities may not be visible to the welder or the Inspector during or after welding. Discontinuities undetectable by visual inspection (VT), or smaller than the standards described in this subclause, are acceptable. All welds are required to be visually inspected and accepted by visual criteria before being subjected to other required nondestructive testing. Nondestructive testing, particularly RT and UT procedures that have the ability to inspect the complete weld volume after the weld is completed, may find small discontinuities that are acceptable to visual standards, but not acceptable to RT or UT standards.

C-8.26.1.1 Cracks. Cracks are not allowed even if subsequent weld passes will cover them or if located in an exclusively compression area. Cracks are prohibited because they are sharp planar defects that concentrate stress. Cracks in tension zones of bridge members can be expected to grow by fatigue, provided the stress level and number of stress cycles is sufficient. They may grow to critical size and cause brittle fracture if not discovered and repaired.

There are three main types of cracks. "Hot" cracks form upon solidification and are generally confined to individual weld passes in single and multipass welds. "Cold" cracks are caused by hydrogen and occur after weld solidification is complete. Fatigue cracks generally take years to form as a result of concentrations of stress at the weld metal or base metal adjacent to weld defects, notches, or design details.

Except for ESW and EGW, solidification "hot" cracks in all welds should be discovered when the welding slag is removed. They are generally limited to individual weld passes, although they may coalesce to form larger cracks. Hot cracks are usually longitudinal cracks in the center of the weld pass. Since the last part to solidify in an ESW and EGW joint is the center of the single-pass weld nugget, hot cracks in these welds are generally confined to the center of the weld and do not show at a surface. RT or UT is used to inspect for the presence of hot cracks in electroslag and electrogas welds.

Cold cracks are generally discovered after the weld has been allowed to cool and has been at ambient temperature for several hours or days. Cold cracking is most common when partially completed welds have cooled down before there is adequate time to diffuse hydrogen from the weld and HAZ. Cold cracks can be found in both completed and uncompleted welds, provided the weld region has cooled sufficiently to allow the cracks to form. Hydrogen-assisted cracking does not occur while the weld region remains at elevated temperatures. While hydrogen-assisted cracks can be found in the weld or HAZ, and may be parallel or transverse to the direction of welding, they commonly occur near the fusion boundary of the weld and base metal. They are typically the cause of underbead cracking. Cold cracks are more likely to occur under conditions of high restraint.

Both hot and cold cracks may be discovered in the root pass because of the high restraint stresses that are present at that location, and as a result of the rapid cooling that is often associated with the first pass. Hot cracks in the root pass may simply mean the first pass was not large enough to sustain the restraint stress, or may have had an improper width to depth ratio. Cold cracks should not occur if welding conditions avoid introducing hydrogen into the weld zone and proper preheat and interpass temperatures are provided (see C-6.2).

C-8.26.1.2 Fusion. To achieve effective stress transfer, sound fusion is essential between the weld metal and all joint surfaces, and between each weld pass and previous weld passes.

C-8.26.1.3 Craters. When weld craters are not filled, a surface shrinkage condition is created that may cause crater cracking. Welds should be full size and of the proper cross section to ensure that the weld is sound, has the required strength, and has produced an HAZ that will not crack. Weld size, at the start and stop and elsewhere along the length of the weld, is an indication of heat input and potential HAZ hardness. Poor weld starts and stops not only create weakness in the weld but also in the HAZ. All welding procedures approved under the provisions of the code are based on an assumption of thermal energy control and arc shielding during welding. The welder is required to produce welds that are sound and of the required dimensions at the start and stop as well as throughout their length.

When intermittent fillet welds are allowed by design, the weld profile outside the limits of required weld length need not have the crater filled. This provision accepts minor crater depressions, but not cracks or other fusion defects at the beginning and ends of intermittent welds, beyond their nominal design lengths.

When terminating a weld, completely stopping forward travel and filling the crater with full current may cause overheating and a rejectable weld profile. Crater filling requires special techniques such as ramping down the current or quickly reversing arc travel directions.

C-8.26.1.4 Profile. Acceptable weld profiles are described in 5.6. Should the completed weld not be within the range of profiles allowed, the technique may have deviated from the approved WPS, the WPS may have been improper, the welding equipment or consumables may have been defective, or a combination of these factors may have occurred. Poor profile makes it more difficult to remove slag, perform NDT, and place subsequent weld passes with adequate penetration and fusion.

Good fillet weld profiles are very important for good fatigue performance. Poor profile configurations may also inhibit the proper transfer of stress to each side of the welded connection, creating excessive concentration of stress at the toes of the weld. Such stress concentrations may be critical in fillet welds or groove welds that are loaded normal to their axis, but are of less concern when the weld is loaded longitudinal to its axis.

C-8.26.1.5 Undercut. Undercut is defined as a groove melted into the base metal adjacent to the weld toe and left unfilled by weld metal. Undercut is evaluated as a notch that will concentrate stress in proportion to the sharpness and depth of the notch. When undercut is normal to applied tensile stress for primary members, the depth of the undercut is restricted to only 0.25 mm [0.01 in]. Crossframes and diaphragms attached to connection plates or stiffeners of horizontally curved girders are considered primary members. Fillet welds attaching connection plates or stiffeners to the web of horizontally curved girders that carry loads from crossframes or diaphragms are considered part of primary members. Undercut is not structurally significant to welds loaded in compression or shear if the undercut is within reasonable workmanship limits, considered to be 1 mm [1/32 in] depth. Due to the difficulty in measurement, no criteria is established for notch acuity. When undercut exceeds specified maximums, repair by light grinding is generally superior to cosmetic weld repairs that may damage the weld or HAZ.

A difficult location for controlling undercut is at the end of web stiffeners where welds made by SAW are terminated. The stiffener sometimes suffers a severe undercut near the snipe (the cut-out that allows the stiffener to clear the web-to-flange welds) because there is insufficient base metal to support the welding heat without melting. Additionally, if the weld runs into the snipe, overlap, slag entrapment, and other fusion defects may result and create future maintenance problems. To overcome these problems, and because it is desirable to terminate stiffener welds away from the web to flange welds, some Owner specifications require stiffener welds to start or stop 5 mm to 10 mm [3/16 in to 3/8 in] from the snipe. The problem of undercutting is not as severe at weld starts, so some welding operators stop the SAW equipment near the center of the girder web and restart the weld from the opposite end to avoid a weld stop near the snipe. Because there is little applied stress on the stiffener at the snipe, localized undercut on an intermediate stiffener near the snipe, unless unusually deep, will not adversely affect performance. Undercut is usually on the stiffener, due to gravity effects of the weld pool, rather than the web where undercut in tension areas can be critical. After all appropriate steps have been taken to limit the amount of undercut, the Engineer may elect to avoid unnecessary weld repairs and allow increased amounts of localized undercut on stiffeners near snipes.

C-8.26.1.6 Piping Porosity. Historically, the AWS Welding Codes, including D1.1, have not concerned themselves with porosity in fillet welds unless the porosity breaks through the surface of the weld. Subsurface piping porosity in fillet welds may be so extensive, with little indication of porosity problems at the surface, that the welds may crack. This subclause was prepared specifically for the *Bridge Welding Code* to deal with the problem of potentially dangerous amounts of porosity in fillet welds that do not appear at the surface.

Porosity is defined as cavity-type discontinuities formed by gas entrapment during solidification. Piping porosity occurs when gases escape to the surface as the weld metal solidifies, leaving behind a path that appears as a hollow tube. When these gas vent holes are observed in weld surfaces, it is an indication that there is too much gas being produced, or that the weld has solidified too fast to let the gas escape, or both. Frequent small piping porosity (pinholes) in fillet weld surfaces, or large piping porosity at any time, are an indication that something is wrong with the welding procedures, surface conditions, or welding consumables.

Because porosity is a rounded discontinuity, it is much less likely to initiate fatigue cracking than planar discontinuities. Fatigue tests have shown that significant individual porosity and piping porosity may occasionally act as initiation sites for fatigue cracking. Piping porosity that extends to the surface is much more damaging to fatigue life than individual small, subsurface spherical porosity. However, examination of bridges in service have not revealed that the porosity allowed by the code is a significant cause of in-service fatigue cracking.

Web-to-flange fillet welds are to be made on base metal that has all mill scale removed. Stiffener and other fillet welds may be made through tight mill scale, possibly producing gas. However, filler metals and welding procedures are available to produce sound welds under both welding conditions.

Piping porosity can also be an indication of a problem with the WPS, or that the welding procedure is not being properly controlled. One possible correction, after the elimination of all possible sources of joint contamination such as moisture and oil, may be to raise the preheat, keeping the weld pool molten longer to allow the gases to escape. The combination of welding heat input and preheat is not to exceed the manufacturer's recommendations or the limits on controlled variables contained within the PQR, whichever governs the WPS.

When more than a few scattered porosity vents are present in fillet weld surfaces, it is an indication that there may be extensive subsurface porosity. Provisions are made by this subclause for a subsurface investigation of fillet welds, at mid-throat depth, after the surface weld metal has been removed. Weld soundness is determined by excavation and visual inspection because fillet welds cannot be effectively inspected by RT or UT.

(1) When large or frequent gas vents (piping porosity) in fillet weld surfaces are present, or other conditions indicate that subsurface porosity may be extensive, a subsurface inspection is necessary.

(2) After the fillet weld surface is removed to mid-throat depth, porosity may be revealed that is much more extensive than at the surface. Compared to surface porosity, a larger volume of porosity can be present in the weld at this mid-throat level and still be considered acceptable. Surface porosity measurements were used as an indication of potential subsurface porosity problems. When viewed at the mid-throat level, every pore is included in the sum of the diameters of piping porosity measured.

When porosity exceeds the limits of these specifications, the weld is removed and replaced. It is important to identify problems with porosity early and make necessary corrections to the WPS, or the materials preparation, as necessary to keep gas-related discontinuities to a minimum. Other solutions include the use of lower deposition rates and the use of active fluxes. As with all repairs, extensive weld removal and rewelding is expensive, and if not done properly, may damage the base metal.

C-8.26.1.7 Underrun. Most fillet welds are intended to be equal leg isosceles triangles of weld metal. The plans may require fillet welds with unequal legs for special applications. Single pass fillet weld shapes and sizes are controlled by gravity, the location and orientation of the welding electrode(s), and the total welding heat input per unit length. Size can be increased or decreased by adjusting the travel speed, wire feed speed, and/or current. In multipass fillet welding, the size and shape of the final weld is determined by the sequence, location, and size of individual weld passes. Weld bead sequence provides a support for each subsequent weld pass. Fillet weld size and contour control requires skill and careful monitoring of the welding procedure.

The horizontal shear between most components of bridge members that are joined by fillet welds is generally a small percentage of the ultimate shear capacity of the fillet welds.

Fillet weld size is often governed by minimum weld size requirements. Procedures selected for fillet welds ensure that each pass has sufficient heat input to fully fuse to adjacent base or weld metal and that the HAZ will not be unacceptably hardened. Minimum heat input requirements generally control minimum fillet weld size. Once a fillet weld is completed, a size deficiency (implying unacceptable HAZ hardening) may be correctable by preheating and depositing another weld pass with sufficient heat input to modify the original weld pass and HAZ; but this may lead to significant residual stresses and distortion. In case of deficient fusion or to modify the HAZ without oversizing the weld, the deficient weld should be removed and rewelded.

Fillet weld size should be carefully monitored during the original welding. Small "cosmetic" passes are not allowed, so if underrun is sufficient to require repair welding, the minimum heat input for each pass satisfies Tables 4.1 or 4.2, or 7.12, as applicable. This subclause provides a rational method for dealing with slight localized underruns in size that have virtually no effect on strength, performance, or the quality of the HAZ. Underrunning in size is not allowed at the ends of girders where the horizontal shear stress is the highest.

C-8.26.1.8 Piping Porosity in CJP Tension Joints. CJP groove welds carrying applied tension, including welds subject to reversal of stress, are not allowed to have any visible porosity in the surface of any weld pass. Piping porosity is an indicator that more significant piping porosity may be present below the surface. Corrections should be made when defects are first noted during welding, not after the weld is completed and when repair will be much more difficult. So that welders and Inspectors will know where these provisions apply, tension welds should be identified on the plans and shop drawings.

For groove welds other than CJP groove welds in applied tension, the limits for piping porosity are the same as that for fillet welds. Rather than remove the weld to mid-depth, as in fillet welds, groove welds may be nondestructively tested using RT or UT to determine the existence and volume of both rounded and piping porosity. The limits for such porosity are provided in 8.26.2 and 8.26.3.

C-8.26.1.9 Time of Inspection. Inspection of completed welds may begin immediately after the welds have cooled, except for the high strength quenched and tempered Grade HPS 690W [HPS 100W] steel. Other aspects of visual inspection are performed before and during welding. The Grade HPS 690W [HPS 100W] steel listed in this subclause is required to be subjected to a final acceptance inspection not less than 48 hours after the weld is completed. As the strength levels of steels increase, so does the concern that hydrogen may cause cracking. Most hydrogen-assisted cracks in quenched and tempered steels occur within the first 48 hours, even though hydrogen-assisted cracks have been known to occur much later under some unusual conditions. The waiting period specified in this subclause is considered to be reasonable. It will ensure that hydrogen-assisted cracks have had a chance to form, but does not interfere unnecessarily with the continuation of construction.

C-8.26.2 Radiographic (RT) and Magnetic Particle (MT) Inspection. Evaluating the quality of welds as specified in this subclause is done by examining either images on radiographic film or indications of discontinuities at or near weld surfaces as highlighted by magnetic particles. It is the intent of the code that RT and MT indications of discontinuities be treated essentially the same, even though they are performed and interpreted differently.

Indications of discontinuities in radiographs are the result of changes in the attenuation (scatter and absorption) of penetrating radiation. Discontinuities such as porosity, lack of fusion, slag, and cracks in the weld metal are less dense than solid steel, allowing more radiographic energy to penetrate the joint and expose the film. Indications of discontinuities are seen as gray or black areas in the radiograph. To reliably detect unacceptable discontinuities, the radiographs provide the required radiographic sensitivity and film quality, and the technicians that review the radiographs need to be skilled and thorough in their examination. Technicians also use proper illuminating equipment and review radiographs under conditions of subdued light to see all significant images in the radiographs.

Radiographs are essentially plan views of the contents of groove welds, as seen from the top or bottom, so lengths and widths of discontinuities are easily measured. When discontinuities are elongated vertically, parallel to the inspecting radiation as in the case of piping porosity, all one sees in the radiograph is the top or plan view of the discontinuity. Tight cracks and other planar discontinuities may appear gray in a radiograph, or may not be detected at all, if the inspecting radiation is not aligned with the plane of the discontinuity. The radiographic image gives no indication of actual discontinuity size under these conditions.

Discontinuities may be distorted, or enlarged, in radiographs when part, or all, of the radiographic film is exposed by radiation that has penetrated the weld at an angle that deviates significantly from 90°. The greater the angularity or misalignment of the inspecting radiation, the greater the distortion of images of discontinuities in the radiograph. When this occurs, the required image quality indicators (penetrameters) will also be distorted. If, for example, penetrameters that measure 12 mm by 38 mm [1/2 in by 1-1/2 in] are longer or wider in the radiograph, it's reasonable to expect that discontinuities in areas of the radiograph adjacent to the penetrameter will be similarly distorted (see Clause 8, Part B).

Indications of discontinuities in radiographs are expected to properly represent the plan view dimensions, length and width, of the actual discontinuities. It is not possible to determine the through-thickness height or location of a weld discontinuity by reviewing radiographs. There is no accurate way to determine the depth of a discontinuity below the surface, or to determine if more than one discontinuity is located above another in the cross section of the weld. Although specific discontinuities such as cracks, lack of fusion, slag, and porosity have recognizable forms in radiographs, through-thickness discontinuity dimensions cannot be determined without further testing by UT, or by measuring after successive excavations.

When radiographic inspection is performed as required by the code and the radiographs meet all code requirements, indications of weld discontinuities in the radiographs should accurately represent the plan view size of the discontinuities.

Magnetic particle indications of discontinuities may be large or small, sharp or fuzzy, depending on the strength of the magnetic field that has been interrupted, the orientation of the discontinuity in relation to the magnetic lines of flux, the size of the discontinuity, and the closeness of the discontinuity to the surface. Subsurface discontinuities, especially when using AC power may not be discovered by MT. Even with rectified DC, MT may only penetrate 2 mm to 5 mm [1/16 in to 3/16 in]. Discontinuity size cannot be judged solely on the size of the MT indication. To determine the full extent of a discontinuity that produces an MT indication, it may be necessary to excavate by progressive grinding or machining down to the discontinuity.

MT and RT indications of weld discontinuities are not the same, even though the acceptance criteria are the same under the provisions of this subclause. Figures 8.8 and 8.9 refer to both groove weld size and fillet weld size and may be used, as appropriate, to determine acceptance criteria when less than perfect fusion exists between the weld and base metal or between weld beads. Radiographic testing of fillet and PJP groove welds is only appropriate in rare instances as an investigative tool, and is not normally performed by Inspectors (see 8.7.4).

C-8.26.2.1 Welds Carrying Tensile Stress. The radiographic weld quality standards of this code are identical to the provisions of AWS D1.1. These standards had their beginning in the ASME Boiler and Pressure Code, Paragraph UW-51, and were modified and adopted for bridges in the late 1950s. In the Boiler Code, there was no concern for ends of welds, or intersections of web-to-flange welds in bridge members, where there is a concentration of stress. The Boiler Code, at that time, limited the maximum discontinuity size to one-third the minimum thickness joined, placed limits on the proximity of discontinuities to each other, and required that the accumulated length of discontinuities not exceed the thickness joined, or size of the weld, in a length of six times the thickness. The criteria was also established based on the best quality of welds that were being produced at the time and the capabilities of the inspection process, rather than the quality needed to sustain the loading and service condition.

For welds carrying tension, Figure 8.8 establishes the maximum discontinuity size and the required separation between discontinuities, based on the size of the discontinuity and the proximity of the discontinuity to other discontinuities or areas of high residual or applied stress. All discontinuities are viewed as potential sites for fatigue crack initiation, on the assumption that even a rounded discontinuity will sharpen and grow if subjected to enough cycles with a sufficient stress range. Cracks of any size are never allowed to remain. Other discontinuities less than 1.6 mm [1/16 in] in size, as viewed in the radiograph, are considered innocuous, provided their cumulative dimensions are within limits (see 8.26.2.3). Other discontinuities are acceptable or rejectable based on type, size, and location. Discontinuities equal to or greater than 1.6 mm [1/16 in] in size are not allowed within dimension "C" of a flange edge, or the toe or root of a web-to-flange weld, because of the high residual stress in those areas. Restrictions on discontinuity size in areas adjacent to flange edges, or subject to high stress near intersecting welds, is considered in terms of fracture resistance since they are more susceptible to brittle fracture than areas that are completely surrounded by base metal.

C-8.26.2.2 Welds Carrying Compressive Stress. Many material and workmanship requirements of the code are based on a concern for discontinuities initiating fatigue cracking, and eventual failure by brittle fracture. When the plans identify welds that will be subject to only compressive stresses, some weld quality standards can be relaxed without fear that there will be any adverse effect on performance or safety. This subclause allows radiographed welds subjected only to compression to contain discontinuities that are roughly twice the size of those allowed in tension groove welds. Discontinuities are also allowed to exist closer to plate edges for compression welds, compared to the "C" dimension criteria for tension welds.

C-8.26.2.3 Discontinuities Less Than 1.6 mm [1/16 in]. Individual discontinuities less than 1.6 mm [1/16 in] in size as seen in the radiograph are considered innocuous, and are usually porosity or small slag inclusions. However, when the sum of the maximum discontinuity dimensions in any lineal 25 mm [1 in] exceeds 10 mm [3/8 in], the weld is considered defective and repairs are necessary.

C-8.26.2.4 Limitations. The weld quality figures indicate that maximum discontinuity size and minimum clearances are proportional to weld size, up to a 38 mm [1-1/2 in] weld. Beyond a 38 mm [1-1/2 in] weld size, the criteria remains constant for discontinuity size and clearance. The figures are not to be extrapolated.

C-8.26.2.5 Annex K Illustration. Annex K illustrates the requirements of this subclause. Annex K illustrates that all welds are not required to be perfect, and also assists in the interpretation of these provisions.

C-8.26.3.1 Acceptance Criteria. The ultrasonic testing acceptance criteria listed in the code are in addition to the visual inspection standards and any MT, PT, or RT required by code or the contract documents. When ultrasonic testing of welds is required, welds are accepted or rejected based on the amplitude of reflected sound, measured in decibels. The number of decibels of ultrasound reflected from a discontinuity may give little or no indication of the type of discontinuity, its size, or the possible effect of the discontinuity on bridge performance. The ultrasonic testing acceptance criteria specified in the code are separate from and cannot be compared to any other weld acceptance criteria.

(1) Welds subject to tensile stress under any condition of loading are ultrasonically acceptable if they conform to the acceptance requirements of Table 8.4. The tensile stress referred to is applied stress, not residual or secondary stress. Table 8.4 was designed based on the assumption that discontinuities reflect sound in proportion to the severity of their adverse impact on performance. When the present ultrasonic testing standard was being developed in the late 1960s, it was assumed that radiographic inspection produced a 2% sensitivity. The ultrasonic testing acceptance-rejection standards of Table 8.4 were initially determined mathematically, in an effort to cause rejection of a discontinuity whenever the through-thickness dimension and length were greater than that allowed by the RT provisions of the code. Little thought was given to misalignment of the inspecting sound beams, other than to treat 60° and 45° search units differently than 70° transducers. It was assumed that a specific reflector size would produce a specific indication rating, and that acceptance or rejection could be based on indication rating, length, and location (see C-8.7). An indication rating, as described in Annex E, is simply the amplitude of reflected sound compared to a calibrated amount of initially transmitted sound, after corrections have been made for sound losses due to attenuation (absorption by the steel). A direct mathematical conversion of discontinuity size to decibels of reflected sound, using these assumptions, produced excessively restrictive acceptance standards for welds in thin steel. Changes were made to Table 8.4 in the late 1970s to make acceptance of welds in thin material less restrictive, and to reduce the number and extent of unnecessary repairs previously mandated.

There is no reliable relationship between weld discontinuity type, orientation, size or severity, and the indication rating. However, no other workable method of ultrasonically testing welds in bridge members has been developed and none is referenced by the code. Research has shown that welds that are ultrasonically tested as specified in the code and accepted or rejected based on the standards of Table 8.4 are very unlikely to contain defects that will impair bridge safety or fatigue life. However, more than amplitude alone should be considered in the acceptance or rejection of welds based on UT.

(2) In general, the acceptance standards for compression welds described in Table 8.5 are four to six decibels less critical than the acceptance standards for tension welds listed in Table 8.4. A decrease of six decibels in the indication rating is roughly equivalent to doubling the theoretical size of an acceptable discontinuity. Table 8.5 is the same as that used in AWS D1.1 as the acceptance standard for statically loaded, nontubular welds in buildings. The compression weld standards of the code are conservative.

C-8.26.3.2 Indications. It is recognized that discontinuities do not generally reflect ultrasound in proportion to the effect of the discontinuity on the integrity of the weld. Three additional testing and evaluation instructions are provided in the following numbered provisions so that major discontinuities are not missed or mistakenly accepted based on ultrasonic tests. All nondestructive methods are subject to some significant inherent limitations. The sizing and characterization of discontinuities in weldments often cannot be done accurately by amplitude alone, as required by the current code provisions. Discontinuities that may lead to failure are reliably detected by the prescribed scanning procedures, but may not accurately be identified as rejectable. Under some conditions, cracks produce amplitude responses that do not give an accurate indication of their size or effect on the integrity of the welded joint. If indications remain on the display as the probe is moved significantly in the required scanning direction normal to the discontinuity and adjusted for the scanning amplitude, discontinuities should be considered unacceptable until a more detailed evaluation can be accomplished. These precautions have justified the preparation of this subclause as follows:

(1) Ultrasonic testing has the ability to detect discontinuities and to accurately determine their location within the weld or adjacent base metal. UT can also determine the length of discontinuities with sufficient accuracy to estimate the effect of the discontinuity on performance. However, UT has considerable difficulty determining the discontinuity through-thickness height, even though efforts have been made to increase the accuracy of this measurement, because the height of elongated discontinuities is critical to performance in a fracture mechanics analysis. As the search unit (transducer) is moved forward and back in a scanning movement normal to the weld axis, shown as scanning movement B in Figure 8.7, a consistent indication of a reflector on the display indicates the presence of a discontinuity with considerable through-thickness height. This provision is designed to warn that when an indication remains on the display during scanning as described, there is a likelihood that the discontinuity has considerable height in the weld cross section and may be a crack or a crack-like defect such as a lamination or lack of fusion.

(2) 70°, 60°, and 45° transducers are used in angle-beam ultrasonic testing. That means that the sound beam is 20°, 30°, or 45° misaligned from being perpendicular to the most critical discontinuity orientation, depending on the search unit used. 60° and 45° transducers can produce sound beams normal to weld preparations that have complementary angles. This produces increased sensitivity when there is concern for the quality of fusion at initial joint groove faces. However, the most critical discontinuity orientation is normal to the applied tensile stress, which is normal to the base metal surfaces. Fusion discontinuities at prepared joint surfaces, normal to the inspecting sound beam, generally produce very high amplitude responses in proportion to their size. This converts to very low indication ratings and generally results in the weld being rejected under the provisions of Table 8.4. The discontinuity may or may not seriously affect performance, depending on size and type of discontinuity. When a defect is normal to the surface of the joint and completely surrounded by sound metal, there is a likelihood that it will be difficult to detect. Almost all of the sound may be reflected away with essentially none reflected back to the transducer. Fortunately, most cracks are somewhat irregular and facets of the surface provide enough reflected sound to indicate their presence. If there are indications of discontinuities with significant through-thickness height, regardless of amplitude, a crack may be present, and soundness should be verified by other wedge angles and locations or alternate inspection methods or tests.

(3) Planar discontinuities become increasingly difficult to detect as angular misalignment with the UT beam exceeds 7°. Slight irregularities in the surface and at the top and bottom of even planar discontinuities help to make them more visible. Scanning is done at very high amplitudes so that poor reflectors, which may be critical defects, may be detected. Scanning levels are described in Tables 8.4 and 8.5. When reflectors remain on the display during scanning using Movement B, the weld should not be accepted until other tests have verified that it is sound. The image of a reflector with considerable through-thickness height will appear to move across the display as the sound path is changed by forward and backward movements of the transducer. This is sometimes referred to as a "walking image". Thin elongated discontinuities with little through-thickness height do not produce this type of indication, so forward and backward movements of the transducer cause their image to disappear. There is a sharp peak in signal amplitude when the sound beam is focused on the most reflective portion of the discontinuity.

C-8.26.3.3 Scanning. Except in unusual conditions, web-to-flange welds are designed to carry only horizontal shear stresses. Fillet welds and CJP groove welds have the same design fatigue life when carrying only shear stress. When horizontal shear is the only applied design stress in CJP web-to-flange groove welds, it is less essential that weld soundness meet all requirements specified for CJP tension groove welds in bridges. Minor discontinuities, parallel to the applied stress, will have little adverse effect. Acceptance of CJP web-to-flange welds is allowed based on the compression weld standards of the code and a material thickness that is 25 mm [1 in] greater than the actual web thickness. This provides adequate weld soundness, and avoids unnecessary repairs that may create more serious weld defects or fatigue problems.

(1) While discontinuities parallel to the applied stress are treated more leniently, discontinuities normal to applied stress are not. Scanning Pattern E is used to discover discontinuities normal to applied stress. Discontinuities, when discovered, should be evaluated to the tension weld standards of the code based on actual web thickness. This is a conservative requirement and is justified by the high residual stresses at this location, and also because a transverse crack in a longitudinal weld carrying shear is serious. Cracks, if present, should also be verified by visual inspection and MT. The weld described is tested to a more lenient standard because the flange is thicker, even though the web and flange have the same residual and applied stress at any common point. Care should be taken not to require unnecessary repairs based on misinterpretation of these provisions.

(2) When portions of web-to-flange welds will actually carry applied tensile stress normal to the weld axis, they should be identified on the plans and on the shop drawings so that all parties will verify the welds meet all requirements for tension groove welds (see C-8.7).

C-8.26.4 Liquid Penetrant Inspection. PT is an aid to visual inspection. The size of PT indications is not always a reliable guide to the size or nature of the discontinuities they represent. When discontinuities are discovered by PT, remove all traces of dye and developer and evaluate the discontinuity visually. Localized, progressive excavations by grinding or machining may be necessary to accurately size and characterize discontinuities. High steel temperatures and crevices on the surface may make PT less reliable.

C-8.26.5 Timing of NDT

C-8.26.5.1 Time of Testing. MT, UT, and PT are allowed to be performed as soon as the welds have cooled, except for Grade 690 [100] and 690W [100W] steels. PT may not provide accurate indications if performed while preheat is maintained.

C-8.26.5.2 Grade HPS 690W [HPS 100W] Steel. When Grade HPS 690W [HPS 100W] high strength quenched and tempered steel is welded, final acceptance testing should not be done until at least 48 hours after completion of the weld, including repairs. Subclause 8.26.1.9 places the same restrictions on visual inspection. These requirements are based on a concern that hydrogen-assisted cracks may form after inspecting and testing, if performed immediately after cooling. Preliminary testing may begin sooner. If unacceptable discontinuities are found prior to the 48-hour elapsed time, it is not necessary to delay repairs, however, repair methods may also cause crack initiation.

C-Table 8.1. The NDT acceptance criteria are workmanship standards and not based on fitness for purpose. The criteria reflect the level of workmanship that can be expected in a bridge shop.

The AASHTO LRFD Bridge Design Specifications define main or primary members. Typical fillet or PJP groove welds that require testing are any welds to web or flange, and welds connecting components of cross frames or diaphragms for curved bridges. Typical joints in compression or shear include web-to-flange welds, stiffeners to webs or flanges, and lap joints.

C-Tables 8.4 and 8.5. The ultrasonic acceptance-rejection criteria listed for welds subject to tensile and compressive stresses are based on the same testing methods and assumptions. Tension weld standards are generally 6 dB more sensitive, representing a theoretical discontinuity size of approximately half that allowed for compression welds. The Class C criteria reflect the fracture mechanics principle that surface discontinuities are roughly twice as sensitive to brittle fracture as buried discontinuities of equivalent size. Class B and C discontinuities are required to be separated as stated in Notes 1 and 2. These requirements are similar to the RT provisions of Figures 8.8 and 8.9, except that for UT, restrictions are not placed on discontinuity size in areas adjacent to the toe, or root, of any intersecting flange to web weld as stated in 8.26.2.1. The weld quality provisions for RT and UT were intended to be identical, but minor differences have resulted from differences in the testing methods.

Note 3 of Table 8.4 reflects concern that unfused, smooth root faces are poor reflectors, similar to smooth cracks. Because CJP groove welds are required to be backgouged to sound metal and verified visually before welding the second side, discontinuities of this type should not be present. However, unless proper backgouging is verified with MT, the increased sensitivity required by the note will apply. This note also does not apply to repairs, which do not have root faces.

Note 4 warns of the tests necessary to ensure that discontinuities with significant through-thickness size are not missed, or incorrectly evaluated, based on amplitude alone.

The acceptance-rejection criteria of Tables 8.4 and 8.5 are grouped by thickness because the indication rating is representative of through-thickness size. The greater the thickness of the CJP groove weld, the greater the weld area and therefore the greater the size of the allowable discontinuity. The Tables were initially designed to duplicate Figures 8.8 and 8.9 and to reject weld discontinuities that exceed 2% of the thickness for the lengths stated, but until the discontinuity height is 7% of the thickness or greater, detection and rejection by UT may be unreliable.

The different acceptance-rejection indication ratings for 70°, 60°, and 45° transducers are based on an assumed relationship between the sound path and the plane of the discontinuity. The search unit is made up of a transducer and an angle-beam sound wedge that is used to produce the required search angle. The different acceptance levels, based on an assumed sound misalignment, are not precise. When the discontinuity orientation is not clear, testing should be done using multiple search unit angles and acceptance-rejection decisions should be made using the values listed for the largest angle search unit. Adding 3 dB and 5 dB to the sensitivity of the 60° and 45° search units because of an assumed misalignment is not appropriate. The sound beam from these search units may be normal to the plane of the discontinuity, or at least as well aligned with the reflecting surfaces as sound from a 70° search unit.

The ultrasonic testing provisions of this code were originally issued in AWS D1.1-69. It is understood that there are errors in the theory upon which the testing procedures were developed. Still the UT method provides reproducible results and has been effective in discovering and rejecting most harmful defects. Efforts to develop better procedures are ongoing.

The testing provisions as provided in the code apply only to CJP groove welds subjected to applied stress normal to the weld throat, except as provided in 8.26.3.3. Search unit size and shape conform to 8.15.7.2. Smaller and differently shaped transducers produce amplitude responses that cannot be used to determine weld acceptance or rejections under the provisions of this code.

Rejectable weld and base metal indications can be verified by careful progressive excavation. If, upon investigation using proper lighting and magnification as necessary, a visible discontinuity cannot be found, ultrasonic testing may not have been done properly.

For ESW and EGW, high welding heat inputs create very large grain structure, making interpretation of UT much more difficult. Grain boundaries may reflect sufficiently to appear as defects, although excavation may not disclose any discontinuity.

C-9. Stud Welding

C-9.1 Scope

Stud welding is unique among the approved welding processes in this code. Not only are the arc length and the weld time automatically controlled by the welding equipment, but a significant production proof test is required. With correctly set equipment, good workmanship, and proper technique, the stud welding process can produce a large number of essentially identical sound welds. Because of the production proof testing, qualification based on Clause 7 and written WPSs is not required. This is a basic difference from the other approved welding processes in this code, therefore stud welding has been placed separately in Clause 9.

This subclause includes testing to establish mechanical properties and the qualification of stud bases by the stud manufacturer, testing to establish or verify the welding setup (essential variables), and testing to qualify specific applications and the welding operator, as well as inspection requirements.

C-9.2 General Requirements

General requirements prescribe the physical dimensions of studs and describe the arc shield and stabilizing flux to be used. These stud base assemblies are qualified by the manufacturer as described in Annex D of this code.

C-9.2.1 Dimensions are provided for the manufacture of the studs, with rigid tolerances to assure compatibility and proper operation with the stud welding equipment. The finished height of the as-welded stud is approximately 3 mm to 5 mm [1/8 in to 3/16 in] less than the manufactured stud length, with stud length reduction less for smaller diameter studs than for large diameter studs.

C-9.2.2 The purpose of the arc shield (ferrule) is: (1) to concentrate the heat of the arc in the weld area, (2) to restrict the flow of air into the weld area, controlling oxidation, (3) to confine the molten metal to the weld area, (4) to prevent the charring of adjacent materials, and (5) to shield the operator from the arc.

C-9.2.3 The purpose of the flux at the tip of the stud base is to stabilize the arc and to hinder or prevent the formation of oxides and other undesirable inclusions in the molten weld pool, created primarily from impurities on the base metal surface but also present in the atmosphere and within the steel itself.

C-9.2.4 The purpose of the stud base qualification testing described in Annex D is to verify that the manufacturer's design of the stud base, with the use of the stabilizing flux tip and the particular geometry of the stud end, in combination with the appropriate arc shield, will provide suitable strength and quality when used in properly set stud welding equipment. Only the common application of the flat (plate surface horizontal) welding position requires testing by the manufacturer. The manufacturer may also perform stud base qualification tests through decking, but these welds are also subject to qualification testing in conformance with 9.6.

C-9.2.5 A quality stud finish is needed for proper functioning with the stud welding equipment. Cracks and other sharp discontinuities in the shank of the stud may lead to cracks in the stud weld itself.

Small radial cracks at the periphery of the stud head, also called bursts, do not adversely affect the structural strength, corrosion resistance, nor other functional requirements of headed studs. The bursts are typically caused by the expansion of small, undetectable seams in the surface of the rod or wire from which the stud is made, expanded by the heading function during manufacture. In some cases, bursts are caused by the radial stresses from the expansion of material during heading. Large bursts may be indicative of deeper seams within the shank of the material that may have gone undetected during visual inspection.

C-9.2.6 To allow verification that the studs to be used and the welding essential variables are within the boundaries of the testing performed and the manufacturer's recommendations, the Engineer may require test data from the Manufacturer's Stud Base Qualification testing (see Annex D10 for the manufacturer's standard test data).

C-9.2.7 AASHTO M 270M/M 270 Grade (A709/A709M) HPS 690W [HPS 100W] steel is heat treated. The heat from stud welding may reduce base metal static or dynamic mechanical properties. For example, thin quench and tempered steel may have reduced tensile properties, and thicker quenched and tempered steels are more likely to have higher hardness and reduced notch toughness in the stud weld HAZ. Underbead cracking is possible. For these steels, the use of preheat in conjunction with the stud welding may be necessary to reduce the high HAZ hardness and reduce the risk of cracking. The Engineer should evaluate applications where studs will be welded in members subject to cyclic tensile stress or stress reversal. The Qualification Test of 9.6 verifies only that the stud itself is acceptable on the steel used, not that the steel will have satisfactory properties.

C-9.3 Mechanical Requirements

Type A studs have a lower strength and are for general purpose use, so they are not permitted to transfer design shear in composite construction. The higher strength studs, Type B, are used as an essential component of composite beam construction.

C-9.3.1 The material described provides suitable mechanical properties for the manufacture, welding, and performance of studs. Other ASTM A108 bar stock grades may be more difficult to manufacture, be unsuitable for welding, or fail to have the strength and ductility required for proper stud behavior.

C-9.3.1.1 Only Type B studs have a minimum specified yield strength, necessary for proper in-service performance.

C-9.3.1.2 Testing for steel strength may be performed after the cold finishing operations. The cold working of the stud surface during drawing and finishing increases the strength of the material, but also reduces its ductility. The heat generated from the stud manufacturing operations is not enough to affect either the strength or ductility of the finished product below that of the cold finished steel.

C-9.3.3.2 The manufacturer's most recent quality control data, obtained within the six month period preceding delivery adequately represents the studs in lieu of lot testing and traceability.

C-9.3.4 If quality control reports are not provided, mechanical testing is performed by the Contractor or manufacturer on the studs provided. The Engineer should determine the number of tests performed based on the quantity of studs required and the homogeneity of the studs supplied.

C-9.3.5 Testing of individual studs or a selection of studs based on diameter and length may be required by the Engineer. Such testing is in addition to the testing previously provided by the manufacturer or Contractor under the provisions of 9.2 and 9.3, and is at the Owner's expense.

C-9.4 Workmanship

The fillet weld profiles shown in Figure 5.4 do not apply to the flash of automatically timed stud welds. The expelled metal around the base of the stud is designated as flash in conformance with Clause 3 of this code. It is not a fillet weld such as those formed by conventional arc welding. The expelled metal, which is excess to the weld required for strength, is not detrimental but, on the contrary, is essential to provide a good weld. The containment of this excess molten metal around a welded stud by the ferrule (arc shield) assists in securing sound fusion of the entire cross section of the stud base. The stud weld flash may have nonfusion in its vertical leg and overlap on its horizontal leg, and it may contain occasional small shrink fissures or other discontinuities that usually form at the top of the weld flash with essentially radial or longitudinal orientation, or both, to the axis of the stud. Such nonfusion, on the vertical leg of the flash, and small shrink fissures are acceptable.

C-9.4.1 Studs with surfaces contaminated with the materials described may have inadequate electrical contact with either the welding equipment or the base metal, or both, resulting in welds with unacceptable porosity, lack of fusion, inclusions, and other discontinuities in the stud weld.

C-9.4.2 The materials described may cause porosity, lack of fusion, inclusions, and other discontinuities in the stud weld. A galvanized surface, because zinc has a relatively low temperature melting point, may cause a low-strength area within the completed weld.

C-9.4.3 Foreign materials present on the base metal may cause porosity, lack of fusion, inclusions, and other forms of weld discontinuities in the stud weld. Moisture and coatings contribute hydrogen that adversely affects the characteristics of the HAZ. Extra caution is urged when welding through decking because there may be areas of moisture present between the layers of material that is not readily detected with visual observation.

C-9.4.4 Arc shield moisture may cause steam explosions, porosity, and in rare cases, underbead cracking.

C-9.4.5 In order to meet the design requirements for shear transfer, actual stud placement needs to be close to the locations specified by the contract. When studs are closely spaced, they behave like one large stud rather than as individual studs. Studs placed very close to the edge of a part may be affected by arc blow during welding, resulting in inadequate weld strength and quality. Tear-out of the base metal is also possible if the stud is very close to the edge and loaded in the direction of the edge.

C-9.4.6 Following stud welding, used arc shields are to be removed and a visual inspection made by the welding operator. This visual inspection should be performed as soon as practical after the stud is welded, in order to avoid a large number of defective studs should the equipment have malfunctioned.

C-9.5 Technique

C-9.5.1 The general characteristics for a stud welding power source are: (1) high open-circuit voltage in the range of 70 V to 100 V, (2) a drooping output voltage-ampere characteristic, (3) a rapid output current rise to the set value, and (4) high current output for a relatively short time. Power sources for SMAW DC and other power sources that do not have constant voltage characteristics are generally suitable.

The stud gun consists of a body, a mechanism to lift the stud and then plunge it into the molten weld pool, an adjustable support for the arc shield holder or grip, and the necessary cables to the stud welding controller.

C-9.5.2 Because of the significant power draw when stud welding, the power source and controller need to be set to weld only one stud at a time. Otherwise, inadequate power may result in significant weld defects.

C-9.5.3 Movement of the stud welding gun during welding may lead to poor fusion, cracking, lack of complete welding throughout the entire base of the stud, and misalignment of the finished stud.

C-9.5.4 Stud welding with base metal temperatures below that specified contributes to excessively rapid cooling of the weld HAZ, increasing the risk of cracking and degradation of the mechanical properties within the HAZ. Moisture present in the weld area contributes to excessive levels of hydrogen and other gases, increasing the risk of HAZ cracking, and also causes excessive porosity, weakening the weld.

C-9.5.4.1 Colder temperatures increase the probability of stud welding problems because of the more rapid cooling of the HAZ, therefore a minimum of 1 in 100 studs are tested with a bend test as described in 9.7.1.4. Lower temperatures also reduce the toughness of the weld and HAZ, therefore the angle of testing is reduced from 30° to 15°. The method of testing should be by bending the stud with a pipe or other hollow device, rather than striking with a hammer. Studs are to be left in the bent position.

C-9.5.4.2 Changes in equipment, equipment settings, or power source require retesting of the WPS to verify its suitability. Because of the high, short cycle power demand, the load voltage and cable voltage drop is greater for stud welding than with the other welding processes. Cable length includes both cable from power source to controller and from controller to stud gun. Adjustment to the operation of the gun itself requires testing to verify that the gun as modified will produce satisfactory welds.

C-9.5.5 Although the use of automatically-timed equipment is generally preferred, the code also allows studs to be fillet welded, at the option of the Contractor, using SMAW. Welders need to be qualified in conformance with Clause 7, Part B, for this application. This option was included for cases where only a limited number of studs are to be welded, with the Contractor's decision usually one of economics, or when the repair or replacement of a limited number of studs is required.

Studs welded by the use of automatically-timed welding equipment or fillet welded by the SMAW process are considered welded by a prequalified WPS.

C-9.5.5.1 The minimum size required provides a weld strength equal to or greater than a weld made using automatically-timed stud gun welding equipment. The minimum heat input concerns are addressed by the use of minimum electrode diameter.

C-9.5.5.2 The electrode diameter is specified to help ensure that minimum heat input is provided. The minimum preheat requirements of Table 6.3 also apply. Out-of-position welding may require the use of smaller electrodes, therefore the heat input of these welds should be evaluated.

C-9.5.5.3 Most studs have chamfered bases and a flux ball attached to the tip that protrudes beyond the end of the stud to initiate the arc. Welding with the flux ball in place would leave a significant gap at the root of the fillet weld, contributing to possible fusion and porosity discontinuities, as well as an undersized effective vertical leg. The flux needs to be removed or sufficiently flattened to provide a solid fit between stud and base metal.

C-9.5.5.4 Although most SMAW electrodes have adequate tolerance and fluxing for moderate amounts of mill scale and rust, all rust and mill scale are removed by grinding for this application. Even tight mill scale is not acceptable (see C-9.4.1, C-9.4.2, and C-9.4.3).

C-9.5.5.5 The electrode diameter specified in 9.5.5.2 assumes that the preheat requirements of Table 6.3 are also satisfied. Inadequate preheat contributes to higher HAZ hardness and increased hydrogen levels, possibly causing a degradation of HAZ mechanical properties and hydrogen-induced underbead cracking.

C-9.5.5.6 The visual inspection requirements of 8.5 are to be met, including several tasks performed before and during the welding. The weld quality requirements of Clause 5 and the visual inspection provisions of 8.26.1 are to be satisfied. No other NDT is normally required.

C-9.6 Stud Application Qualification Requirements

C-9.6.1 Prequalification. Special conditions where Application Qualification Requirements apply include studs using modified arc shields, studs welded in the vertical or overhead positions, studs welded through decking, and studs welded to other than AASHTO M 270M/M 270 (ASTM A709/A709M) steels.

Modified arc shields may be required when studs are welded to nonflat surfaces. Vertical stud welds are particularly prone to undercut-like discontinuities at the top of the stud. Overhead stud welds may have undercut about the perimeter of the stud. Since these and other special cases are not covered by the manufacturer's standard stud base qualification tests, the Contractor is responsible for the performance of these Application Qualification tests, serving a purpose similar to the WPS qualification testing required for the other welding processes.

Stud welding through decking is not prequalified because of the many testing variables that would be inherent for the Manufacturer's Stud Base Qualification Requirements: the number of plies, the thickness of decking, the coating type, and coating thickness. The heaviest metal decking thickness, whether one or two plies, along with the thickest coating (galvanized if used), would provide a worst case, not necessarily applicable to every stud on the project, to verify the adequacy of the equipment to be used. Many manufacturers do perform such testing for standard thicknesses and coatings of decking, as provided in Annex D5.1.

C-9.6.2 Responsibilities for Tests. Testing for non-prequalified applications is the responsibility of the Contractor. However, the testing may be performed by organizations other than the Contractor. For decking, many manufacturers perform such testing for standard thicknesses and coatings of decking, as provided in Annex D5.1. Nonstandard applications such as vertical or overhead welding may also have been previously tested. Engineers may accept evidence of previous special Application Qualification tests, where new work would fall within previous limits, with added assurance provided by the preproduction tests using the specific stud welding setup as described in 9.7.1.

C-9.6.3.1 Test specimens for Application Qualification may be performed on any of the AASHTO M 270M/M 270 (ASTM A709/A709M) steels, regardless of the steel being used for construction. However, should the steel receiving the studs be a steel not described in 1.2.2, approved by the Engineer, then the testing should be performed on the steel being used or a representative sample.

C-9.6.4 Number of Specimens. All ten specimens are to be welded consecutively, using the welding variables as detailed in 9.6.3.2. All ten specimens need to pass the prescribed tests, and if any of the ten specimens fail, another ten are tested using the original or appropriately revised welding variables and settings.

C-9.6.5 Tests Required. For headed studs, either the bend test or tension test may be performed. For threaded studs, the torque test may also be used (see Annex D, Figure D.1A for the locations of acceptable fractures in the shank of the stud and unacceptable fractures in the weld).

C-9.6.6.2 Torque Test. The torque test may be used for threaded studs. The torque value listed is based on the lubrication provided from residual standard cutting oils. The tension produced on the stud will be highly dependent on the effectiveness of the lubrication provided. Stud threads that are unlubricated or rusty will produce less tension for a given torque value, and will not test the stud with the tensile force expected. It is not necessary to relubricate the stud with new cutting oil provided some residual oil is present. Studs that are relubricated with a more efficient lubricant will produce much higher tensions for a given torque, and may fail the stud in tension. However, failure in this case will typically occur in the threads and not in the weld, therefore the stud weld is considered acceptable. These studs may have already achieved the tension expected prior to failure. Figure 9.3 does not state the tension expected based on the torque value used, but the torque provided, with residual cutting oil lubrication, should stress the stud to about 55% of its tensile capacity based on the gross cross-sectional area of the stud.

C-9.6.6.3 Tension Test. Using the tension test, the stud is tested to failure. The actual tension required to fail the specimen need not be measured, as the acceptance criteria for this test is based solely on the fact that the weld did not fracture and that the fracture occurred in either the stud or base metal. It is assumed that the stud has the minimum mechanical properties described in 9.3.1.1.

C-9.6.7 The data required for Application Qualification tests is similar to that required of the manufacturer in Annex D, subclause D10, with the addition of the welding variables as recorded in 9.6.3.2.

C-9.7 Production Control

Testing is normally required for the first two studs of each day's or shift's production, or with any modification in the setup changing any one of the following: stud gun, timer, power source, stud diameter, gun lift and plunge, total welding lead length, or changes greater than 5% in current (amperage) or time. Users unfamiliar with any of these terms should refer to AWS C5.4, *Recommended Practices for Stud Welding*.

C-9.7.1.1 Because the suitability of the WPS has been documented through either prequalification from the manufacturer's stud base qualification testing of Annex D, or through the application qualification tests of 9.6, this test is used only to verify the proper setup of the equipment. Preproduction testing may be done on representative material of thicknesses approximating that of the production piece, or may be done on the production member itself unless problems arise.

At the very high currents used in stud welding, it is very important to have adequate lead size and good lead connections. Stud gun settings may be inadvertently changed between shifts or through handling. For these reasons, this testing is expected at the beginning of every work shift, or whenever changes to setup occur (see 9.7.2).

C-9.7.1.2 Separate plates may be used for preproduction testing at the Contractor's option. When stud welding problems occur, testing on plates is required by 9.7.1.5 to minimize the damage done to production members until the proper procedures have been established.

C-9.7.1.3 Stud welding flash around the entire base of the stud provides indication of complete welding beneath the stud. Lack of complete flash indicates problems such as improper lift or plunge, stud hangup in the gun, movement of the stud gun, insufficient welding heat, or failure to use the stud gun perpendicular to the surface. These problems are to be corrected before proceeding with production welding.

C-9.7.1.4 Bending. At temperatures below 10°C [50°F], some stud and base materials lack adequate toughness to pass the hammer test.

C-9.7.1.5 If either of the two initial preproduction tests fail to pass the visual flash examination or the bend test, adjustments should be made followed by a second preproduction test with two studs. This second test may be done on either the production member or other representative material. If either of the second pair of welds fail the preproduction test, then conduct all subsequent adjustments and preproduction tests on representative material, not the production member, to avoid damage and repair from failed tests.

C-9.7.2 Production Welding. Production welding may begin as soon as preproduction testing is satisfactorily completed. Any adjustments to the equipment, changes in welding lead length, or welding essential variables such as current or time beyond 5% require the repeating of the preproduction testing using full visual inspection for complete flash and bend testing (see C-9.5.4.2).

C-9.7.3 In cases of missing flash, bend testing of the stud in the direction opposite the missing flash may cause the stud weld to fail, necessitating repair following the provisions of 9.7.5. The Contractor may opt to repair the weld by using a fillet weld, provided that all the provisions for fillet welding in 9.5.5 are followed. The fillet weld need not extend completely around the stud base, but is expected to extend at least 10 mm [3/8 in] beyond the missing flash.

C-9.7.4.1 The successful completion of the preproduction testing of 9.7.1 also qualifies the welding operator. The welding operator's qualification remains effective following the provisions of 7.21.4.

C-9.7.4.2 Welding operators not performing previous preproduction testing may be qualified by performing the preproduction testing described in 9.7.1.3 and 9.7.1.4.

C-9.7.5.1 Components Subject to Calculated Tensile Stress. Discontinuities created by stud failure may propagate from applied tensile stress. Removal of a shallow defect in a tensile area may be accomplished by finishing the area smooth when repair welding of base metal is not needed. When evaluating remaining net section, only the element with the failed stud or studs is included, so for a plate girder or rolled beam, just the top flange area is compared.

C-9.7.5.3 Stud Replacement. 7.7.7.1 prohibits combining FCAW-S with another welding process unless qualification testing is done. 7.5.2 limits SAW with active flux to single and two-pass welds which may be insufficient with significant tear-out.

C-9.7.5.4 Any replacement studs are to be inspected using a bend test of 15°, except for threaded studs that employ a tension test with an applied torque.

C-9.7.5.5 On areas visible in the completed structure, all remnants of broken studs or welds should be removed and the base metal repaired if necessary and then finished flush.

C-9.8 Inspection Requirements

In addition to visual and bend tests by the welding operator, representative studs are routinely visually inspected and/or bend tested by the Inspector.

C-9.8.1 Any production stud not exhibiting full flash about the perimeter of the stud base is normally bend tested to approximately 15°. Any stud repaired using SMAW is normally tested in the same manner.

C-9.8.2 Any stud requiring bend testing is bent away from the missing flash. Missing flash is an indication of incomplete fusion or filling at the base of the stud, and the weakest part of the stud weld in resisting bending.

C-9.8.3 Threaded studs not exhibiting 360° of flash about the base are tested using torque methods as described in Figure 9.3. The stud is to be considered adequate if the stud reaches the specified torque (see C-9.6.6.2 for discussion of the torque values).

C-9.8.4 At the Inspector's discretion, studs may be selected for 15° bend testing, even if exhibiting full flash about the base of the stud.

C-9.8.5 Studs embedded in concrete perform adequately in the bent position. For studs not embedded in concrete, the studs may be bent back into position when required. The use of heat is not allowed to assist in straightening.

C-9.8.6 When the stud failure rate is high, the Engineer may require action to bring the acceptance rate to a suitable level. Such actions may include repeating of stud base testing, qualification testing, more frequent preproduction testing, or other adjustments to the welding operations.

C-12. AASHTO/AWS Fracture Control Plan (FCP) for Nonredundant Members

The ANSI/AASHTO/AWS D1.5-95, *Bridge Welding Code*, was the first edition to include a clause for the fabrication and welding of fracture critical nonredundant members as part of the code. This clause was the joint effort of AASHTO and AWS and was intended to replace the *Guide Specifications for Fracture Critical Non-Redundant Steel Bridge Members*, which was issued by AASHTO in 1978, including subsequent interim revisions.

C-12.1 General Provisions

This commentary on the Fracture Control Plan (FCP) for Nonredundant Members is intended to generate a better understanding in the application of the Plan to the design and construction of non-redundant bridges. The Fracture Control Plan should not be used indiscriminately by designers as a crutch "to be safe" and to circumvent good engineering practice. Fracture critical classification is not intended for "important" welds on non-bridge members or ancillary products or on bridge members that do not meet the definition of Fracture Critical Member (FCM); rather it is only intended to be for those members whose failure by fracture would be expected to result in a catastrophic collapse of the bridge. The safety and reliability of a bridge is governed by material properties, design, fabrication, erection, inspection, maintenance and usage.

Historically, the following fabrication-related factors have contributed to bridge member failures: design details resulting in notches or stress concentrations; design details requiring joints difficult to weld and inspect; lack of base metal and weld metal toughness; hydrogen-induced cracks; improper fabrication, welding and weld repair; and unqualified personnel in inspection and NDT. Attention to all of these factors is essential. Too much attention to any one item will not overcome the effects of a deficiency in any other item.

The implementation of the Fracture Control Plan will help ensure that steel bridges with critical tension components will serve a useful and serviceable life over the period intended in the original design. FCMs are defined in more detail in 12.2 and are basically tension members or portions of members in a bridge whose failure could cause a partial or complete collapse of the bridge with the associated risks to public safety. The majority of bridges do not have FCMs, but it is most important to recognize them and implement appropriate fabrication safeguards when they do exist.

In addition to the requirements contained in Clause 12, all other provisions of the code apply to the construction of FCMs. If there is a conflict between this clause and other provisions of the code, this clause takes precedence.

In 1995, the ANSI/AASHTO/AWS D1.5-95, *Bridge Welding Code*, was issued, including Clause 12 that specifically addresses additional requirements for FCMs, based on the 1978 AASHTO Fracture Control Plan. The D1.5 code contains provisions to ensure reliable control of weld quality. Major changes from the 1978 AASHTO plan (and later modifications) include the following:

(1) Alternative to lot testing criteria for filler metals.

(2) Testing of FCAW and SAW welding consumables for diffusible hydrogen in conformance with AWS A4.3 by the gas chromatograph method or under mercury rather than the glycerine method.

(3) More extensive controls on exposure of welding consumables to atmospheric moisture.

(4) Prequalification of SMAW WPSs using certain low-hydrogen electrodes.

(5) Qualification testing of WPSs for FCMs fully consistent with D1.5 requirements for WPSs used on nonfracture critical members.

(6) Extension of WPS qualification testing period of validity from one to three years.

(7) New tack welding requirements.

(8) Preheat levels based on heat input and diffusible hydrogen levels, as well as steel grade and thickness.

C-12.2 Definitions

C-12.2.1 Fracture Control Plan (FCP). The Fracture Control Plan referenced and detailed in Clause 12 of this document was introduced in the 1995 edition and replaced the "Guide Specifications for Fracture Critical Non-Redundant Steel Bridge Members-1978" developed by AASHTO.

C-12.2.2 Fracture Critical Member (FCM). Fracture critical members are defined as the tension members or tension components of a bending member of a bridge whose failure would be expected to result in the collapse of the bridge. For the purposes of this code, "collapse of the bridge" may include the entire superstructure or a significant portion that would threaten public safety and/or leave the remaining structure unusable, for example, failure of a pin supporting a suspended truss span. A fracture critical member may be a complete bridge member or it may be a part of a bridge member such as a web or tension flange.

The identification of such components is, of necessity, the responsibility of the bridge designer because virtually all bridges are inherently complex and the general categorization of every bridge and every bridge member is impossible. However, to fall within the fracture critical category, the component will be in tension due to externally applied loads.

Examples of complete fracture critical bridge members are tension ties in arch bridges and tension chords in truss bridges, provided a failure of the tie or chord could cause the bridge to collapse. Some complex trusses and arch bridges without ties do not depend on any single tension member for structural integrity; therefore the tension member would not be considered a fracture critical member.

Critical tension components of members may also occur in flexural members. Continuous multi-span girder bridges will have portions of the girder with either the top or bottom flange in tension. In a simple span girder bridge, the area from the neutral axis to the bottom flange will be in tension. At any given location, one flange of a flexural member is in tension and, therefore, would be a critical component if a failure could cause collapse of the bridge, e.g., a structure using a single welded box girder or two welded I-girders. The web of a flexural member in the above applications is always partially in tension and can similarly be a critical component.

Tension members or member components whose failure would not cause collapse of the bridge are not fracture critical. Compression members and portions of bending members in compression may be important to the structural integrity of the bridge, but do not come under the provisions of this plan. Compression components do not fail by fatigue crack initiation and extension, but rather by yielding or buckling.

The plan provides for additional quality of material and increased care in the fabrication and use of the materials to lessen the probability of fracture from crack initiation and extension under in-service loading of critical tension components.

C-12.2.2.1 Attachments. The provisions of this subclause describe what minimum size attachment is to be considered a fracture critical member, if it is welded to a fracture critical member or member component. This attachment length is the minimum length needed to transfer stress into the member and has been established as the minimum length that may cause cracks to propagate from the attachment into the fracture critical member because of the flow of stresses between the two. Short members will not attract enough stress to make the attachment fracture critical.

AASHTO *LRFD Bridge Design Specifications*, 8th Edition, 2017, 6.6.2.2—Fracture-Critical Members states that "Any attachment, except for bearing sole plates, having a length in the direction of the tension stress greater than 4.0 in. that is welded to a tension area of a component of a FCM shall be considered part of the tension component and shall be considered fracture critical."

The exclusion of bearing sole plates from FCM designation is based upon the low localized stress associated at end of spans, for interior supports of continuous girders, because the attachment is in an area of compression. AASHTO Table 6.6.2.1-1 designates bearings, filler plates, sole plates, and masonry plates, as secondary members, exempt from FCM designation.

C-12.2.2.2 Welds. Longitudinal stiffeners and other accessories that are welded to the compression area of webs or flanges are not fracture critical. However, welds attaching transverse stiffeners to the tension area of webs would be fracture critical. It is the weld and not the stiffener that is classified as Fracture Critical. In compression, crack formation and extension would be limited.

Bearing sole plates welded to the tension flange are exempted because they are located in regions of low or zero tensile stress. Additionally, preheating to fracture critical requirements may be harmful to some bearing materials.

C-12.3 Contract Documents

C-12.3.1 Prebid Designation of FCMs. The Engineer is to ensure those members or member components that are fracture critical are designated on the contract documents, allowing the Contractor to incorporate related material, fabrication, erection, and inspection costs into their bid.

C-12.3.2 Shop Drawings. The shop drawings are prepared by the Contractor. The Engineer should, in general, simply specify the type and size of weld, e.g., complete joint penetration (CJP), partial joint penetration (PJP), or fillet, and leave the details of the particular joint geometry to the Contractor. The Contractor is in the best position to select details of welded joints that best fit the material configuration and shop's capabilities.

C-12.3.2.1 Engineer's Review. The Engineer is responsible for the review of the shop drawings only to ensure general conformance with the plans and specifications, including identification of the fracture critical members and that material lists and weld procedures are in conformance with this Fracture Control Plan.

The Engineer also judges the suitability of a WPS for a particular welded assembly or connection. The code requires that the Engineer review and accept written WPSs prior to their use in production. This review may be made in conjunction with review of the shop drawings.

C-12.3.2.2 Acceptance. Review and acceptance of the Contractor's shop drawings and WPSs confirms the Contractor's understanding of the design drawings and contract requirements. Such acceptance does not change contract requirements, transfer responsibility for the execution of the work to the Engineer, or endorse errors or omissions on the shop plans that conflict with the contract plans and specifications.

C-12.4 Base Metal Requirements

C-12.4.1 Approved Base Metals. The steels described in this subclause are approved for welding in bridge construction by the AASHTO Subcommittee on Bridges and Structures. These steels are considered weldable and may be purchased with CVN test values that are suitable for bridge service at temperatures provided for in the three separate AASHTO Temperature Zones. The steels described in 1.2.2 may be joined successfully by adhering to the provisions of this code. Other steels may need different controls to produce sound, crack-free welds with the required mechanical properties. Steels not described in 1.2.2 require an appropriate investigation of weldability and approval of the Engineer before being used in this code (see C-1.2.2 for additional information on this subject).

C-12.4.2 Optional Base Metal Requirements. Special material requirements described in the contract documents that are not normally provided by the steel producer should be described in the mill order so that the mill is aware of all metallurgical and physical property requirements before production begins. Listing of all special requirements on the mill order also provides the Engineer, Contractor, Inspector, and other interested persons with verification that all FCM material requirements have been understood and satisfied.

C-12.4.2.1 Optional Through-Thickness and Low-Sulfur Requirements. Lamellar tearing is defined as the separation or tearing on planes parallel to the rolled surface of the base metal from strains induced by weld metal shrinkage in the through-thickness direction. Lamellar tearing occurs in the through-thickness direction because the base metal has limited ductility in that direction. With strains applied in the through-thickness (Z) direction of thick members, the Engineer should evaluate each location and determine if improved through-thickness (Z) properties should be required at specific locations. If possible, the Engineer should provide alternate details to eliminate through-thickness loading, especially on thick plates. Normally, sulfides are the most detrimental type of inclusions that contribute to lamellar tearing, however, silicates and alumina may also influence susceptibility to lamellar tearing. Base metal with low sulfur (less than 0.010%) and improved through-thickness properties can be specified, typically at an increased cost. Locations in a structure where this type of material is required are to be identified on the contract drawings or specified in the contract documents, and shown on the shop drawings.

C-12.4.2.2 Optional Heat Treatment. Material performance properties such as the notch toughness and strength of the completed weldment and base material will normally be affected by heat treatment. It is the responsibility of the Engineer to understand these effects and specify what, if any, heat treatment is required so that the material and completed member will perform satisfactorily.

C-12.4.3 Base Metal Identification. Die stamp impressions can cause stress concentrations that could lead to fatigue cracking. For this reason, only low-stress or ministress die stamps are allowed. The imprint in the steel should be as light as is practical to still allow easy reading.

C-12.5 Welding Processes

C-12.5.1 Approved Processes. Structures welded with SMAW, SAW, and FCAW processes using low-hydrogen practices and methods compatible with the fabricator's shop equipment and expertise have a long history of satisfactory service. These processes are routinely used for production welding when high levels of toughness and quality are required.

When metal cored electrodes were first introduced, they were classified under AWS A5.20/A5.20M, *Specification for Carbon Steel Electrodes for Flux Cored Arc Welding*. As part of FCAW-G, such filler metals were permitted for use by this code. Metal cored electrodes were thus permitted for use in the fabrication of bridge members for both redundant and nonredundant structures, when considered part of FCAW-G. The metal cored electrodes, however, did not leave behind a substantial slag covering, one of the characteristics of FCAW processes. In this regard, it was more like GMAW. Consequently, the A5 Filler Metal Committees reclassified metal cored electrodes under GMAW Filler Metal Specifications. This code was changed to incorporate the latest definitions of the welding processes.

GMAW is permitted to be performed with the metal cored electrodes without any special restrictions, even though in previous editions of the code, GMAW was specifically prohibited for the fabrication of FCMs unless specifically approved by the Engineer. This continues to be the case when GMAW is performed with solid electrodes, but is not the situation if metal cored electrodes are employed.

C-12.5.2 Prohibited Processes and Procedure Restrictions. GMAW may be used when approved by the Engineer. GMAW may be performed using a variety of modes of transfer including spray, globular, pulsed arc, and short-circuiting transfer. Short-circuiting transfer, also called short arc or dip transfer, is a low energy mode of transfer. While ideally suited for sheet metal applications (often less than 1 mm [1/32 in] thick and typically less than 6 mm [1/4 in] thick), it may lead to a condition where fusion to the base materials is not achieved. This is typically called cold lap, unacceptable because no fusion exists between the weld metal and the base metal. For thin material applications, the energy input needs to be controlled to avoid burn-through, and short circuiting transfer is appropriate for these conditions. When applied to heavier materials such as those typically used for bridge applications, special precautions need to be implemented to preclude the development of these fusion discontinuities, including the cleanliness of the material, the proper selection of shielding gases, welder technique, etc. Root passes in open root joints (typically not applied to most bridge applications, but may be incorporated into bridges that utilize tubular members), are commonly made with GMAW-S.

Subclause 1.3.6 requires the Engineer's approval for the use of GMAW-S for all applications. For Fracture Critical Members, the Engineer's approval is required for all GMAW WPSs using solid wire, regardless of mode of transfer. This allows the Engineer to verify that the parameters selected are not likely to result in the inappropriate use of short-circuiting transfer.

GMAW may be performed with either solid electrodes or with tubular electrodes that contain metal powders. The second type of electrode is typically called a metal cored electrode. When initially introduced in the late 1970s, metal cored electrodes were originally classified as flux cored electrodes for FCAW-G welding. As such, they were used for bridge applications and other structural applications through the 1980s and early 1990s. The AWS A5 Filler Metal Committee determined that it was more appropriate to classify the welding performed with metal cored electrodes as GMAW, as compared to FCAW, because metal cored electrodes did not leave behind the residual slag blanket consistent with the FCAW process. Typical metal cored electrodes now have classifications such as E70C-6, where the "C" designates a cored electrode. Formerly, the same electrodes were typically classified as E70T-1 flux cored electrodes.

C-12.6 Consumable Requirements

C-12.6.1 Diffusible Hydrogen of Weld Metal. The resistance to brittle fracture of a welded connection is dependent on eliminating conditions that might reasonably be anticipated to lead to the initiation of cracks. The Fracture Control Plan limits the addition of unacceptable levels of diffusible hydrogen during the fabrication of fracture critical members or member components by controlling minimum preheat and interpass temperatures and regulating the type and handling of consumables.

C-12.6.1.1 Electrode Optional Supplemental Diffusible Hydrogen Designator Requirements for Welding. The "H" designator indicates the maximum average diffusible hydrogen content in milliliters per 100 grams (mL/100 g) of deposited weld metal. H4 means a maximum of 4 mL/100 g and H16 means a level of 16 mL/100 g. Higher strength steels have a higher risk of hydrogen-induced cracking, therefore higher strength weld metal requires lower diffusible hydrogen levels for this Fracture Control Plan. Solid electrodes for GMAW are typically not tested for diffusible hydrogen because the electrodes have no flux to absorb moisture. Solid GMAW electrodes are assumed to be capable of meeting the requirements for diffusible hydrogen designator H4.

C-12.6.1.2 Special Requirements. Special provisions that a filler metal manufacturer may require to ensure that weld metal will meet the diffusible hydrogen requirements of this code and the Fracture Control Plan may not be covered in this code. All additional requirements or special precautions required by the filler metal manufacturer in excess of those required in this code are described in complete detail in a written procedure.

C-12.6.3.1 Matching Strength Groove Welds. When matching strength filler metals are required, the code requires that the minimum notch toughness of the filler metal be as described in Table 12.1.

C-12.6.3.2 Undermatching Strength Welds. When matching strength filler metal is not required, the Engineer is encouraged to use, where appropriate, lower strength, high ductility weld metal that will reduce residual stress, distortion, and the risk of cracking or lamellar tearing in adjacent base metal HAZs. The code requires a minimum notch toughness of the undermatching strength filler metal of 34 J @ –30°C [25 ft·lb @ –20°F]. Undermatching is most often associated with fillet welds on steels with a minimum specified yield strength greater than 345 MPa [50 ksi].

C-12.6.4.1 SMAW Electrodes. SMAW electrodes are to be purchased in hermetically sealed containers for fracture critical work. If low-hydrogen SMAW electrodes are furnished in hermetically sealed containers and the containers are undamaged, the electrodes should provide acceptable low-hydrogen performance when the containers are opened and the electrodes are used without prolonged exposure to the atmosphere. Instructions for the proper care and storage of electrodes are provided in this Fracture Control Plan.

Tack welds made without preheat may have an increased tendency to crack due to the faster cooling rate, higher HAZ and weld metal hardness, and the increased amount of diffusible hydrogen. The use of hydrogen controlled electrodes described in this subclause will further reduce the probability of cracking in the HAZ and in the weld metal (see C-12.13).

C-12.6.4.2 Sealed Containers. A hermetically sealed container is defined as a container that has been closed in a manner that provides a nonpermeable barrier to the passage of air or gas in either direction. If the hermetic seal is damaged, the electrodes will not be protected from exposure to the atmosphere and may absorb atmospheric moisture, and therefore cannot be used to make fracture critical welds. Redrying of electrodes from containers with damaged hermetic seals is prohibited for FCM welding. The risk that drying electrodes that have absorbed excess moisture may not completely restore the electrode coating to the original manufactured condition is too great. They may be used for nonfracture critical members. Electrodes with damaged flux coatings will not provide proper shielding during welding and should not be used for any welding, whether on fracture critical or nonfracture critical members.

C-12.6.4.3 Storage. At the minimum required holding oven temperature of 120°C [250°F], the electrode coating will not pick up moisture from the atmosphere.

C-12.6.4.4 Drying Temperatures. Keeping SMAW electrode coatings clean and dry requires the use of electrode drying and storage ovens. Electrodes that have dropped below the minimum required temperatures for excessive periods of time may have picked up excessive moisture, and attempting to restore these electrodes to their original condition may not be a suitable risk.

Electrodes may be redried only once because repetitive drying oxidizes metallic elements in the coating, and may cause cracking or failure of the coating. Low-hydrogen electrodes that are not acceptable for use under the provisions of this Fracture Control Plan, because of their exposure to the atmosphere, can be used for nonfracture critical applications if allowed as described in 6.5.

For carbon steel low-hydrogen electrodes, AWS A5.1/A5.1M, *Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding*, specifies a maximum moisture content in the as-manufactured or as-received condition for low-hydrogen coatings of no more than 0.6% for E70XX, 0.3% for E70XX-R, and 0.1% for E70XX-M. Alloy steel low-hydrogen electrodes covered in AWS A5.5/A5.5M, *Specification for Low-Alloy Steel Electrodes for Shielded Metal Arc Welding*, also have a specified maximum moisture content in the as-manufactured or as-received condition. For the E70XX-X class electrodes, it is 0.4%; for E70XX-R, 0.3%; for E80XX-X electrodes, 0.2%; and for the E90XX-X, E100XX-X, E110XX-X class electrodes, 0.15%.

Experience has shown that the limits specified above for moisture contents in electrode coverings are not always sufficiently restrictive for some applications using the E90XX-X and lower classes. Electrodes of classifications lower than

E100XX-X are subject to more stringent moisture level requirements when used for welding Grade HPS 690W [HPS 100W] steel. All such electrodes are dried between 370°C and 425°C [700°F–800°F] for one hour before use (see 6.5.3). Electrodes of classification below E90XX-X are not required by AWS A5.5/A5.5M to have a moisture content less than 0.15%, and the required drying will achieve at least this moisture level. This precaution is necessary because of the sensitivity of high strength steels and weld metal to hydrogen-induced cracking.

C-12.6.4.5 Storage and Drying Ovens. Opening the electrode oven door to check the temperature of the electrodes will result in somewhat lower readings than actually exist within the oven with the door shut. If an excessive temperature variation occurs because of an unsealed or open door, and high drying or baking temperatures are being used, the temperature gradient may cause the electrode coating to crack. If the temperature gradient is excessive and the baking or drying temperature is high, there may be damage to the electrode flux coating. Using the port hole in the oven door or a thermometer that allows direct temperature readings of the inside oven temperature will allow accurate readings. No material other than electrodes should ever be placed in a storage or holding oven, as this could result in contamination of the rods.

C-12.6.4.6 Maximum Atmospheric Exposure of SMAW Electrodes. Table 6.6 lists the maximum allowable time that electrodes can be exposed to the atmosphere. Longer exposure times may lead to excessive moisture pickup by the electrode coating. Exposure time is based on the strength level of the electrode. Higher strength weld metal will tolerate less hydrogen than lower strength weld metal. Electrodes with the optional supplemental moisture resistance designator "R" may be exposed to the atmosphere for a longer time period as given in 12.6.4.8.

Tests have shown there can be a wide variation in the moisture absorption rate of various brands of electrodes representing a given AWS classification. Some electrodes absorb very little moisture during standard exposure times, while others absorb moisture more rapidly. The moisture control requirements of Table 6.6 are necessarily conservative to cover this condition and ensure that sound welds can be produced.

The time restrictions on the use of electrodes after removal from a storage oven may seem overly restrictive to some users. The rate of moisture absorption in areas of low humidity is lower than that encountered in areas of high humidity. The code covers the most restrictive situations.

C-12.6.4.7 Electrode Exposure Limits. In order to prevent SMAW electrodes from being redried more than once, rod ovens should have separate areas for rods received directly from containers and those being redried.

C-12.6.4.8 Optional Supplement Moisture-Resistant Designators. In order for a low-hydrogen electrode to be designated as low-moisture-absorbing with the "R" suffix designator, electrodes are to be tested by exposure to 27°C and 80% relative humidity for a period of not less than nine hours. These tests are defined in AWS A5.1/A5.1M and A5.5/A5.5M, and are conducted by the electrode manufacturer. The nine hour time period was selected based on a typical workshift length, including mealtime. The moisture content of the exposed covering is not to exceed the maximum specified moisture content for the "R" designated electrode and classification in the appropriate A5.1/A5.1M or A5.5/A5.5M specification. Such electrodes may be used with exposure times of up to nine hours on steels with a minimum specified yield strength of 345 MPa [50 ksi]. For higher strength steels, exposure time is limited to that described in Table 6.6.

C-12.6.4.9 Electrodes for Grades HPS 485W [HPS 70W], HPS 690W [HPS 100W] Steels. When used for fracture critical Grade HPS 485W [HPS 70W], HPS 690W [HPS 100W] steel members, this subclause allows redrying electrodes exposed for periods exceeding the limits of Table 6.6 by one hour or less. The higher redrying temperature range of 425°C to 540°C [800°F to 1000°F] is sufficient to restore the electrode coating to a low moisture level, provided the electrodes were not damp and the ambient atmospheric exposure time was no more than one hour beyond the limits of Table 6.6.

C-12.6.4.10 Production Welding Electrode Usage. How much moisture is absorbed or adsorbed (adheres to the outside but is not absorbed) by the electrode coating depends on the temperature, humidity, storage conditions, and the type of coating of the electrode. Electrodes in small containers open only at the top are partially protected. They will pick up considerably less moisture than electrodes laying unprotected on cold, damp, or dirty steel. Electrodes need to be kept in containers that protect them from contaminants that would make the electrodes unacceptable for use. To reduce the chance of electrodes being exposed beyond the time limits of Table 6.6, the welder is not allowed to remove more electrode than will be consumed within these limits. The shop should maintain written documentation of the times when rods were taken and when rods were returned for redrying.

C-12.6.5.1 Electrode and Flux Packaging. Electrodes and fluxes that have been removed from their protective packaging need to be protected from deterioration and contamination prior to and during their use. Fluxes have to be packaged in moisture resistant packages only, not hermetically sealed containers. Flux manufacturers may provide hermetically sealed containers; however, it is not mandatory. If the flux package has been damaged or left open for long periods, the flux will not be protected from prolonged exposure to the atmosphere, and therefore is not allowed to be used to make fracture critical welds.

C-12.6.5.2 Flux Handling and Drying (Baking). Proper storage and usage practices help ensure that flux will remain in a good, dry condition until used. Flux in undamaged packages stored in a protected dry environment is generally expected to remain in good condition until used, provided the time held in unopened bags is not excessive. However, it is still mandatory to bake the flux dry to remove any possible excess absorbed moisture. After the package has been opened, exposing the flux to the atmosphere, the flux is to be stored, handled, and distributed as described in this subclause for use on fracture critical members.

C-12.6.5.3 Drying and Storage Temperatures. Flux ovens are to be capable of storing and drying flux to the requirements of this Fracture Control Plan. The moisture is to be able to escape from the flux layer and not be trapped within the flux. If the flux layer is too deep, the moisture will not be able to vent to the surface of the flux layer and escape into the atmosphere. Flux consistency may also be affected by uneven drying. Opening the flux drying or storage oven door to check the temperature of the flux oven will result in lower readings than actually exist within the oven with the door shut. Checking the temperature through the port hole in the oven door or with a thermometer that allows direct temperature readings of the inside oven temperature will allow accurate readings.

C-12.6.5.4 Discharge and Refill of Flux Hoppers. Flux in hoppers of welding machines can pick up moisture if left in the equipment for an extended period of time. How much moisture might be accumulated by absorption or adsorption (moisture on the outside of particles that do not absorb moisture) depends on the temperature, exposure conditions, relative humidity, and flux type. Most fluxes are relatively unaffected by moisture, but it is poor practice to resume welding with old flux still in the hopper after a considerable delay. The 10-hour rule was established to prevent continuation of welding with existing flux left in the hopper after the machine has been shut down for more than one shift. The time limit was selected so that the flux did not have to be replaced after suspension of welding during a shift, provided welding with the same machine would resume before the 10 hours had expired.

For example, removal and replacement of flux is not necessary if a machine is consistently in use for two shifts per day, but would be required if the shop is working only one shift per day, or suspending work for a weekend.

C-12.6.5.5 Open Top Flux Systems. Open top flux hoppers allow the atmosphere to be in contact with the top layer of flux without any protection being provided. The top layer (10 mm [3/8 in]) of flux, which may become contaminated if exposed over six hours, is to be removed. Removal is to be done carefully, using either a vacuum system or appropriate tool to avoid mixing the top layer with the flux below.

C-12.6.5.6 Time Limits for Flux Replacement. With the approval of the Engineer, the flux exposure time limits may be extended if the Contractor or manufacturer can demonstrate by testing in conformance with the provisions of AWS A4.3 for diffusible hydrogen that the limits have not been exceeded. The amount of hydrogen absorbed is dependent on many factors, including but not limited to temperature, relative humidity, and the flux hopper system. If test welds made using extended exposure fluxes verify that the diffusible hydrogen for the welding procedure to be used conforms with the optional diffusible hydrogen designator of the filler metal and flux being used, then the exposure time limits may be extended, but the criteria for this extension needs to be fully defined, based on those parameters used for the test.

C-12.6.5.7 Pneumatic Flux Delivery Systems. Unless removed by dryers and filters, compressed air may contain moisture, oil, and other contaminants that can mix with the flux as the air moves the flux through the system. Only clean, dry air should be used to operate pneumatic flux delivery systems. Filtered, dried air should be periodically checked by venting to the atmosphere to verify that it is acceptable for use. To avoid placing moisture or contaminants in the joint, the air should not be aimed directly at the weld joint when venting is done.

C-12.6.5.8 Flux Recovery. Contractors are allowed to recover and reuse flux that has not been melted or contaminated by dirt, moisture, or any other material that will adversely affect welding properties. Flux removed immediately after welding is still hot and dry and may be directly recycled into the system. Before use in production welding, flux not recovered from weldment surfaces within five minutes but recovered within one hour is to be dried at 290°C [550°F] for at least two hours, or following the temperatures and times recommended by the flux manufacturer, to remove any moisture. Flux that falls on the floor or comes into contact with oily steel surfaces is not to be reused because of likely contamination. All reclaimed flux should be passed through screens, and magnets where appropriate, to remove mill scale and other debris.

C-12.6.5.9 Recovered Flux. When fluxes are recovered, they may break into smaller particles as part of the mechanical process of removing the flux from the weld joint and replacing this recovered flux into the flux storage system. Some flux recovery systems will separate flux fines (often called flux flour) out of the system. These fine particles may be of different chemical composition than the bulk of the flux. Excessive flux fines may affect bead shape. Significant differences in composition could affect weld metal mechanical properties. This provision requires that any harmful effects of flux recovery be mitigated by requiring that at least 1/3 of the total flux used be new, properly dried material. The method used by the Contractor needs to be defined in a written document, and followed by the welding operators.

C-12.6.5.10 Gravity Feed Delivery Systems. The Contractor adds new, unused flux in sufficient amounts to make up for all losses. To conform to this requirement in gravity fed systems, at least one-third new flux, by volume, is added to the flux hopper at intervals not to exceed one hour during actual welding.

C-12.6.6 FCAW and GMAW Electrodes. 12.5.2 requires approval by the Engineer to use GMAW with solid electrodes.

C-12.6.6.1 Electrode Packaging. FCAW electrodes that have been removed from their protective packaging are to be protected from deterioration and contamination prior to their use. FCAW electrodes have to be packaged in moisture resistant packages only, not hermetically sealed containers. Manufacturers may provide electrodes in hermetically sealed containers; however, it is not required under this FCP. If the package is damaged or left open for long periods, the hydrogen content may be affected because the flux core, through the electrode's seam, may have absorbed a limited amount of moisture that could introduce excessive hydrogen into the weld.

C-12.6.6.2 Shielding Gas. It is essential that the gas or gas mixtures used to shield FCAW-G be dry. Even a slight amount of moisture in the shielding gas may lead to porosity or hydrogen contamination of the weld. To ensure that the shielding gases are dry, a very low dew point is specified. If there is insufficient moisture in the gas to condense at a temperature of –40°C [–40°F], the gas is dry enough to be used in welding. A dew point of –40°C [–40°F] converts to approximately 128 parts per million (ppm) by volume of water vapor, or about 0.01% available moisture. In addition to certifying conformance to the dew point requirement of the specifications when requested, the Contractor furnishes certification that the gas or gas mixture is suitable for the intended welding use, and is the same gas used for WPS Qualification Testing. These provisions are identical to those of 6.13, except that the manufacturer's certification is required.

No drafts in excess of 8 km/hr [5 mi/hr] are allowed with FCAW-G. Higher velocities may disperse the shielding gas, allowing nitrogen, oxygen, and moisture from the atmosphere into the weld.

C-12.6.6.3 Electrode Storage. Electrodes are to be dry and clean when they are used. Electrode manufacturers package their electrodes in a manner that is intended to allow them to be stored for reasonably extended periods of time without damage from moisture or other contaminants. Once removed from the plastic envelope, the electrodes may pick up moisture, become contaminated by foreign material, or rust. Electrodes that have rusted are unsuitable for welding and should be discarded.

Electrode manufacturers attempt to make their tubular electrodes as impervious to moisture absorption as possible. When welding is interrupted for more than eight hours, electrodes are removed from the welding machines and either returned to protective packaging or placed in a storage oven until again needed. After accumulating 24 hours of exposure, the electrodes are to be reconditioned as required in 12.6.6.5. An identification and monitoring procedure preventing over-exposed electrodes from being used on fracture critical welds is necessary.

C-12.6.6.4 Time Limit Extension for Electrode Exposure. With the approval of the Engineer, the FCAW electrode exposure time limits may be extended if the Contractor or manufacturer can demonstrate by testing, in conformance with the provisions of AWS A4.3, that the diffusible hydrogen limits have not been exceeded. The amount of hydrogen absorbed is dependent on many factors, including but not limited to temperature, relative humidity, shop conditions, and how the electrode is packaged, stored, and handled. If tests on over-exposed wire verifies that the diffusible hydrogen for the WPS to be used conforms with the diffusible hydrogen designator of the filler metal being used, then the exposure time limits can be extended, but the criteria are to be fully defined, based on test conditions.

C-12.6.6.5 Drying Temperatures. Metal reels are recommended for baking unless it can be shown that other type reels are not damaged by the baking temperature. Electrodes may be baked only once because repetitive baking may cause failure of the flux system. If the baking requirements of 12.6.6.5 are in conflict with the electrode manufacturer's recommendations, the manufacturer's recommendations take precedence.

C-12.7 Welding Procedure Specification (WPS)

Current AWS filler metal specifications recognize that weld metal properties may vary widely, depending on electrode size, flux used, current (amperage), voltage, plate thickness, joint geometry, preheat and interpass temperature, surface condition, base metal composition, and admixtures with the deposited metal. Because of the profound effect of these variables, a test procedure is included in the filler metal specifications requiring the same welding conditions for all filler metal manufacturers. This provides a uniform basis to compare weld metal properties to the minimum acceptance criteria set by the A5 Specifications. The welding parameters specified are not representative of all possible production setting and do not allow the producer to vary the current, voltage, and travel speed to optimize weld metal properties.

Although the A5 filler metals specification test requirements are adequate for most applications, they are not considered sufficient for welding primary bridge members. Therefore, this code requires WPSs to be qualified by test as described in Clause 7 and as amended for Fracture Critical Members as described in Clause 12. Low and intermediate strength SMAW WPSs for FCMs are exempt from qualification testing as described in 12.7.1 of the code. WPS qualification tests help ensure that the properties of the production weld metal deposited will provide the strength, ductility, and toughness required by the code.

C-12.7.1 Limited Prequalification for SMAW. Under the FCP, only the listed electrodes of E7016, E7018-1, and E8018-X, including those with "C," "M," and "R" designations, are considered prequalified. The E7028 electrode has inadequate toughness for groove welds under the FCP.

Low and intermediate strength SMAW WPSs are exempt from testing because the methods used to weld in the shop or field are essentially the same as the methods and control of welding variables used during the electrode's certification tests. Qualification testing of high strength SMAW WPSs adds an additional level of safety for high strength welds. Under D1.5, electrode classification tests are run yearly and available for the Owner's review as specified in 6.1.4 and 7.5.

WPSs may use standard geometries of welded joints as described in Clause 4, or use nonstandard joint geometries that have been qualified in conformance with 7.12.4.

C-12.7.2 Groove WPS Qualification. The WPS qualification tests described in this subclause, together with the procedures for control of welding variables listed in Clause 6, Part H, give confidence that welds will have the mechanical properties, quality, and soundness required by the code or contract documents. The CVN test values are to satisfy 12.6.3. for this Fracture Control Plan, rather than the requirements listed in Table 7.3 that applies for the balance of the code.

C-12.7.4 Period of Effectiveness. Because of the nature of Fracture Critical work, the qualification testing for a Contractor's first fracture-critical WPS must have been conducted no more than one year before that procedure is first used in production. Subsequent qualification tests are to be performed at the frequency described in this subclause. Once a project has begun, it is unnecessary to repeat WPS qualification testing simply because the 60-month period since testing has elapsed.

C-12.8 Certification and Qualification

Quality workmanship requires fabrication capability, trained workmen, and effective knowledgeable supervision. The AISC Certification Program evaluates a fabrication plant's general management, engineering, drafting, procurement, operations, and quality control. Each of these areas is divided into sub areas and evaluated for policies, organization, personnel, procedures, facilities and equipment, and past record. The Fracture Critical supplement helps ensure the shop's ability to produce FCMs. The AISC Certification Program for Steel Bridge Fabricators has three categories of certification (Simple, Intermediate, and Advanced) based on structure type, any of which might be appropriate for a fracture-critical structure.

C-12.8.1 Welding Personnel Qualification. The code allows the qualification of welding personnel to remain in effect indefinitely for nonfracture critical welding, provided they have used the process within the past six months. The Fracture Control Plan requires requalification at least annually or for each project. This requirement is more restrictive than for the groove welding of nonfracture critical members. In order to keep the costs of annual requalification to a minimum, the Engineer should consider the option to base the annual requalification of groove welders/welding operators on acceptable radiography of production groove welds. Personnel making Fracture Critical fillet welds and tack welds are qualified in accordance with the standard requirements of Clause 7, Part B. Personnel who are qualified for groove or fillet welding are also considered qualified for tack welding.

C-12.9 As-Received Inspection of Base Metal

Initial visual inspection of all received material is important and is intended to eliminate the possibility that a defective piece supplied by the producing mill will become a part of a fracture critical member or member component. Visually inspecting the piece for discontinuities before fabrication begins helps to avoid later problems, especially if base metal defects are found after welding has been completed, necessitating critical repairs and risking distortion of the weldment during the repair.

C-12.10 Thermal Cutting

This title was changed from "oxygen cutting" to "thermal cutting" in the D1.5-95 code because most mills and fabricating facilities can also perform plasma cutting. It appears that plasma cut edges are equivalent to oxygen cut edges; thus it seems proper to use the common generic term—"thermal cut edge" (TCE).

Surfaces and edges to be welded are expected to be smooth, uniform, and free from fins, tears, cracks, and other discontinuities that might adversely affect the quality or strength of the weld. When metal is cut by shearing, edges are often ragged and sometimes torn or cracked. Laminations at sheared edges sometimes split apart. Sheared edges, because of their rough surface, are difficult to inspect for cracks, laminations, and other harmful discontinuities that may propagate into a weld region. Unwelded edges with such sharp notches could have reduced fatigue life. Universal mill plates may exhibit similar unacceptable surface discontinuities. These stress risers left on unwelded tension member edges may develop into fatigue cracks that could cause the piece to fail in service.

Thermal cut edges are generally superior to sheared edges and avoid many of the conditions that can adversely affect the quality of the welds or reduce fatigue life.

C-12.10.1 Thermal-Cut Edge Requirements. See C-5.2 for a detailed explanation.

C-12.10.2 Magnetic Particle Testing (MT). The yoke method of MT is specified because it avoids the possibility of the magnetizing current arcing the base metal at a prod contact point. Fatigue cracks may initiate from arc strikes caused by prods.

An adjustable probe is much more effective than a fixed yoke. Overall inspection is likely to be more thorough than with prods because the yoke is easier to manipulate and requires less strength and stamina to perform, important for an operator working for long periods of time.

C-12.10.3 Laminar Discontinuities. Laminations are normally parallel to the rolled surface, appearing as planes in the through-thickness of the piece. Laminations exposed at the fusion face of a groove weld are essentially like a crack and may propagate into the weld or base metal during weld cooling or in service. Because the depth of the lamination may be extensive, assuming the lamination will be melted out or suitably fused and closed by welding is not acceptable. If a lamination exists within 300 mm [12 in] of the weld on the edges of the member to be welded, there is the possibility that the welding stresses or the application of design loads may cause the lamination to propagate into the weld metal and HAZ of the base metal.

Welding is prohibited across laminations on fracture critical members or member components because there is the possibility that weld discontinuities or cracks will result.

C-12.11 Repair of Base Metal

C-12.11.1 Rotation of Base Metal. Because Fracture Critical Members or member components require a high level of care when making repairs, base metal repairs should not be made unnecessarily. It is preferable to correct the defect area by means other than welding, if practical.

C-12.11.2 Thermal Cutting. It is acceptable to remove the area of base metal that contains the defect by thermal cutting and to replace it with another piece of suitable approved steel. The relocation of the butt joints from their original detailed location or the addition of butt joints needs to be preapproved by the Engineer. The weld locations are to be documented and recorded on shop drawings submitted for the Engineer's records. For a more detailed discussion on thermal cutting, see C-5.2.5 and C-5.2.6 (see C-12.17 for repairs of base metal made by welding).

C-12.11.3 Repairs. For a more detailed discussion, see C-5.2.5 for base metal repairs and C-12.17 for base metal and weld metal repairs.

C-12.11.4 Replacement. Rather than repairing it, defective base metal may be removed and replaced with new base metal. The material may be of the same or higher strength, with equal or superior toughness and weathering properties, except that Grades HPS 485W [HPS 70W] and HPS 690W [HPS 100W] are not to be substituted for lower strength material. The substitution of these grades of quenched and tempered material for lower strength material would be such an overmatch that it could cause residual stresses and cracking problems detrimental to the structure. All new base material and weld metal is expected to comply with the requirements of this code and the Fracture Control Plan.

C-12.12 Straightening, Curving, and Cambering

Editions of the code prior to 2020 permitted straightening only by heat shrink methods. However, research focusing on the influence of heat and bending strain on the toughness and mechanical properties of steel has revealed that increasing the bend radius to 5.0 times the thickness of the plate and bending the material at room temperature does not significantly degrade the material properties of the plate.[1]

C-12.13 Tack Welds and Temporary Welds

C-12.13.1 Tack Welds. Tack welds are given special attention because they may be crack initiation sites.

C-12.13.1.1 Location. Properly made tack welds, located outside of weld joints, may constitute poor fatigue details. For example, intermittent tack welds on the outside of longitudinal backing inside box sections constitute Category E fatigue details. A continuous tack weld at the same location is a Category B detail. The code requires that all tack welds be made within the weld joint, unless specifically allowed by the Engineer. A continuous tack weld for longitudinal backing would be one example where the Engineer's approval would be appropriate.

C-12.13.1.2 Requirements. Tack welds can be made inappropriately, resulting in fabrication-related cracking. Tack welds are typically made with low heat-input WPSs, typically small in size, and may be small in length. Such welds experience high cooling rates, and cracking under such conditions may occur. Tack welds that are of insufficient size, whether too short or of too small a throat dimension, can crack due to shrinkage stresses, part handling, or subsequent expansion and contraction of the final welding.

Table 12.3 lists four approaches that are allowed for tack welding on FCMs. One involves tack welds outside the weld joint, and requires the Engineer's approval (see C-12.13.1.1 and Table 12.3, Note c).

The first option contained in Table 12.3 is for tack welds intended to be remelted by subsequent SAW. These tack welds should be made small in size, and longer in length, in order to obtain the required strength, and to facilitate subsequent remelting by SAW. The code does not require a test to demonstrate that such tack welds are being remelted by SAW. Moreover, it is acknowledged that other welding processes are capable of remelting tack welds. A large tack weld with a substantial throat dimension is unlikely to be remelted by SAW. Additionally, welding over such large tack welds in the root of a groove can cause subsequent weld quality problems and may affect weld appearance.

[1] Keating, Peter B. and Christian, Lee C. 2012. "*Effects of Bending and Heat on the Ductility and Fracture Toughness of Flange Plate*", Texas Transportation Institute, Report No. FHWA/TX-10/0-4624-2.

The WPSs for tack welds that are remelted by SAW need not be qualified by test, but the code requires that filler metals used to make tack welds be listed in Table 6.1. For FCMs, the code requires that SMAW electrodes used for tacking without preheat are required to meet the diffusible hydrogen requirement in 12.6.4.1. The reason for the omission of WPS qualification for these WPSs is two-fold. First, the subsequent submerged arc remelts and eliminates the tack weld, so its original properties are of no consequence. Secondly, WPSs for tack welds (i.e., small weld sizes) involve low heat input unable to generate the code-mandated strength, elongation, or toughness properties of a WPS qualification test.

No preheat is required for tack welding when the tack weld is remelted by subsequent SAW. Even though the tack weld may be very high in hardness, low in elongation, or may even crack, the remelting by subsequent SAW eliminates this condition.

GMAW may be used for tack welding when the tack welds are remelted by SAW. Normally, with solid electrodes, GMAW welding requires the Engineer's approval for use on FCMs. Because these tack welds are remelted, no such approval is necessary.

The second tack-welding option allowed by Table 12.3 treats the tack weld just like production welds. Preheat is required, the WPS is required to be qualified by test, the minimum weld sizes apply, etc. A minimum length of 75 mm [3 in] is required in order to generate a minimum level of localized heating of the part.

The third option of Table 12.3 is essentially the same as the second option, but deals with tack welds outside the joint. These require the approval of the Engineer.

The fourth option is for tack welds inside the joints that do not conform to the conditions of the first two options. These tack welds are *not* remelted by SAW, nor do they meet the minimum size requirements of the second option. A minimum preheat level of 200°C [400°F] is imposed for these types of tack welds to minimize the potential of hydrogen-induced cracking, even with limited heat input. These WPSs are to be qualified by test and experience has shown that it is unlikely that acceptable weld metal properties be obtained if very low heat input WPSs are qualified. Therefore, the expectation is that the fourth option will rarely be used.

C-12.13.2 Temporary Welds. Temporary welds are welds made to attach a piece or pieces to a weldment for temporary use in handling, shipping, or working on the weldment. Such welds and their HAZs may experience stresses and stress ranges that may initiate fatigue cracks, and therefore are to be removed. Temporary welds may be allowed to remain in place if approved by the Engineer.

C-12.13.3 Weld Removal. Even if finished flush, HAZ and fusion zone discontinuities that remain at tack and temporary weld removal sites can initiate fatigue cracks. Hydrogen-induced cracks may also initiate at low heat input tack welds and remain after their removal. 12.13.1.1 only permits tack welds that will be subsequently covered by production welds. 12.13.3 requires removal of temporary welds and their HAZs to a depth of 3 mm [1/8 in] below the original surface. Per 5.3.7.4(2) and 5.3.8, hardness testing is used to assess HAZ removal, and any cracks present after the 3 mm [1/8 in] removal may be detected by visual and magnetic particle testing. Any cracks found warrant additional exploration and repair. To keep stress raisers to a minimum, a gradual, uniform transition with a smoothly finished surface is necessary.

C-12.14 Preheat and Interpass Temperature Control

Tables 12.4, 12.5, 12.6, 12.7, and 12.8 for preheat under the Fracture Control Plan have added two additional elements not considered for redundant members: the diffusible hydrogen limit of the weld metal deposited by various filler metals, and the heat input from welding. The level of required preheat is therefore a function of the type of steel, thickness of steel, hydrogen level of the filler metal, and the heat input from the welding process.

The grade of steel is one of the variables necessary to determine the required level of preheat because as the carbon content of the steel increases, or as the level of alloy content increases, the degree of hardenability of the steel also increases. The higher the hardenability, the greater the level of required preheat to prevent cracking.

As the thickness of the steel increases, the rate of cooling experienced by the weld in the HAZ also increases, all other parameters being constant. Increased cooling rates may lead to higher hardness of the HAZs and weld metal, justifying increased levels of preheat. Reduced levels of heat input from welding results in faster cooling rates, and justifies higher preheat to preclude cracking.

Finally, as the level of hydrogen in the deposited weld metal increases, the susceptibility to hydrogen-induced cracking increases. Conversely, lower levels of diffusible hydrogen will reduce cracking sensitivity, allowing the use of lower levels of preheat.

To arrive at the preheat tables that incorporate these two additional variables, the subcommittee began with the preheat values described in the 1978 Guide Specifications for Fracture Critical Non-Redundant Steel Bridge Members. The Guide Specification had provisions that would ensure that the allowed electrodes would deposit weld metal with a diffusible hydrogen content that would not exceed approximately 10 mL per 100 g, as measured by the glycerine method. This level of preheat, proven to be adequate by 15 years of fabrication experience, became the required preheat level for WPSs using a heat input of 2.0 kJ/mm to 2.8 kJ/mm [51 kJ/in–71 kJ/in], and for weld deposits that did not exceed 8 mL/100 g, (H8) deposits. This was a conservative approach, as the 1978 Guide Specification provisions did not ensure that H8 weld metal could be achieved. In other words, the levels of preheat were arbitrarily increased slightly, since the H8 requirement would provide lower levels of diffusible hydrogen than were required by the 1978 Guide Specification. A comparison of the Guide Specification values and the D1.5-95 values shows that the 2.0 kJ/mm to 2.8 kJ/mm [51 kJ/in–71 kJ/in], H8 requirements for the given steel thickness and grade are identical to the Guide Specification requirements.

The Guide Specification values were then modified based on a preheat model established by Dr. Yurioka of Nippon Steel. To begin the analysis with the Yurioka model, a chemical composition is required to be known. From the chemical composition, a “CEN” or Carbon Equivalency Number is determined. For the purposes of the code, however, the actual chemical composition of the steel that would be employed is not specifically known. Therefore, the time proven preheat levels of the Guide Specification, for the assumed heat input range of 2.0 kJ/mm to 2.8 kJ/mm [51 kJ/in–71 kJ/in], and the hydrogen level of H8, were used to back into the CEN value that would predict the preheat levels that had been previously required in the guide specification. To do this, 2.0 kJ/mm [51 kJ/in] heat inputs were used, and the lower level of the thickness range was employed. These two measures added in yet another degree of conservatism into the calculations. Once the CEN value was established, the Yurioka model was used to predict what increase in preheat would be required for lower levels of heat input (specifically 1.2 kJ/mm [31 kJ/in]), and what decrease may be allowed for heat input levels of 2.8 kJ/mm [71 kJ/in] or higher. This approach generated specific numbers that would be very difficult to rationally control in a fabrication shop. For the D1.5-95 code, it was decided that the preheat levels would be grouped into 14°C [25°F] increments. To do this, the actual calculations were rounded down 5.5°C [10°F], or up 8.3°C [15°F] in order to develop even increments of 14°C [25°F]. Overall, this approach added another level of conservatism to the calculations.

Using the Yurioka model, the nonrounded values were used to predict the decrease in preheat that would be acceptable with H4 weld deposits, and the increase necessary with H16 deposits. Once these values were established, the aforementioned rounding policy was used.

After all the values were put in a table, the subcommittee exercised some judgment in adjusting numbers to fit a more logical sequence, rounding some figures up 14°C [25°F] in order to provide consistency and some technically logical consistency between all the tables, adding another degree of conservatism.

In some cases, the required preheat levels predicted by the Yurioka models would have eliminated the need for preheat beyond that of normal ambient conditions in most fabrication shops (e.g., approximately 15°C [60°F]). However, this code specifies that, regardless of the predicted preheat, a minimum of 40°C [100°F] should be applied to all fracture critical fabrication. Any value less than 40°C [100°F] were thus increased to this minimum level. This added another level of conservatism to the preheat levels.

For AASHTO M 270M/M 270 (ASTM A709/A709M) Grade HPS 690W [HPS 100W] steel, it was determined that the highest level of diffusible hydrogen allowed should be limited to H8. For this reason, Table 12.8 does not include the H16 category, and H4 and H8 have been combined into one column.

The hydrogen groupings represent the maximum allowable level of diffusible hydrogen. For example, a filler metal capable of delivering weld deposits with 6 mL of diffusible hydrogen per 100 g would be classified as an H8. The preheat levels assume that the hydrogen level is at 8 mL per 100 g even though it is lower than H8. The preheat is established for the maximum allowable diffusible hydrogen level allowed for the particular H classification. For the range of heat input shown, the preheat level is established for the lowest allowable heat input. For the thickness ranges shown, the preheat is based on the thickest material allowed in the range. The preheat is expected to be adequate when all values are at their extreme level. Lower levels of diffusible hydrogen, thinner sections, and higher heat input WPSs within an allowable range will increase the level of safety when the preheat values in the tables are used.

For the D1.5-96 code, new metric tables were developed. The allowable thickness ranges utilized appropriate metric increments of 20 mm [3/4 in] in thickness, and the heat input ranges were converted into a logical metric interval of kJ/mm. It was determined that a preheat interval of 20°C [35°F] was logical. Rather than starting with the U.S. Customary table that had rounding implications and other adjustments built into it, the calculated CEN was used to derive a true metric table. Actual calculated values were rounded to the nearest 20°C [35°F] increment, and the values were adjusted for logical consistency. A minimum value of 40°C [100°F] was established as the lower bound for all fabrication.

C-12.15 Postweld Thermal Treatments

C-12.15.1 Hydrogen Diffusion Postheat. Postheat is used to encourage the diffusion of hydrogen out of the weld and the HAZ. At elevated temperatures, the rate of hydrogen diffusion is exponentially faster than at lower temperatures. For example, approximately the same quantity of hydrogen will be diffused from a 25 mm [1 in] thick weld deposit in one hour when the weld is held at 230°C [450°F] as would occur in two weeks at ambient temperatures. When weld joints are large or severely restrained, when high strength steels are to be welded, or when other conditions suggest that hydrogen-induced cracking could be a problem, postheating should be considered. Postheat is required for most FCM repair welds in groove excavations [see 12.17.6(11)].

C-12.15.1.1 Minimum Temperature Prior to Hydrogen Diffusion Postheat. Hydrogen-induced cracking only occurs at relatively low temperatures (less than 150°C [300°F] for most structural steels, less than 250°C [480°F] for virtually all steels). To be effective, postheat is applied before the welded joint is allowed to cool below these temperatures. Otherwise, hydrogen-induced cracking can occur before the postweld heat treatment is applied, eliminating any beneficial effects of the treatment. For this reason, this provision requires that postheat be applied, when required, before the welded joint is allowed to cool below the minimum preheat and interpass temperature.

C-12.15.1.2 Hydrogen Diffusion Postheat Temperature Limitations. Postheating effectively eliminates hydrogen-induced cracking from welds and HAZs. Steel that is maintained at 230°C [450°F] or higher will continue to diffuse hydrogen and reduce the risk of cracking even if hydrogen levels and stress are higher than desirable. However, since the exact temperature is not known for all steels and situations, the 230°C [450°F] temperature and holding time is conservative.

C-12.15.2 Postweld Heat Treatment (PWHT). Heating of welds or base metal by external heating sources to postweld heat treatment temperatures that are 480°C [900°F] or higher is considered a postweld heat treatment (stress relief). Properly designed and constructed bridge weldments have excellent fatigue lives without postweld heat treatment. Postheating at temperatures below 260°C [500°F] is primarily done to remove hydrogen and is not considered a stress relief heat treatment.

C-12.15.2.1 Approval. Heating to elevated temperatures and cooling of steel weldments may detrimentally affect toughness and strength, and intergranular cracking may sometimes occur in the grain-coarsened region of the HAZ. It may also aggravate pre-existing discontinuities or allow new ones to form. It is essential that the Engineer approve postweld heat treatments so that the impact on the ability of the member to function as designed can be assessed. Guidelines for stress relief heat treatment are described in 6.4 of this code.

C-12.16 Weld Inspection

C-12.16.1.1 Inspectors. Individuals performing inspections and making decisions about the acceptability of materials and workmanship need documented evidence of qualification. Certification based on successful completion of the AWS QC1 program, *Standard for Certification of Welding Inspectors*, is considered evidence of basic competence. Inspectors qualified as Level II or III by the Canadian Welding Bureau in conformance with the provisions of CSA W178.2, *Certification of Welding Inspectors*, are considered the equivalent of an AWS Certified Welding Inspector, or CWI. Engineers and technicians who, on the basis of their education and experience are considered equal to AWS or CWB certified individuals in their ability to perform inspection functions properly, may serve as Inspectors with the Engineer's approval.

The provision that allows Engineers and technicians to act as Inspectors, when approved by the Engineer, applies to both Contractor and Owner representatives. It is intended to allow highly qualified individuals to perform inspection functions, as necessary, even if they are not certified by AWS or CWB (see 8.1.3).

C-12.16.1.2 NDT Technicians. The code requires personnel performing NDT be certified as an NDT Level II or Level III that has passed a practical examination and is also qualified as a Level II, in conformance with ASNT Recommended Practice No. SNT-TC-1A. These requirements are more stringent than is required for NDT of nonfracture critical members by allowing the testing to be performed only by individuals certified as NDT Level II and working under the supervision of a certified ASNT Level III or by a certified Level III qualified as a Level II. To ensure the capability of the Level III persons, they are required by code to be certified through ASNT testing or the testing equivalent as determined by the Engineer. The term "under the supervision" means that the NDT Level III person will be available, as necessary, will personally oversee and independently verify the NDT Level II technician's work on a periodic basis.

C-12.16.2.1 Tension and Repaired Welds in Butt Joints. The Fracture Control Plan requires that both RT and UT be used in determining the quality of all groove welds loaded in tension transverse to their axis. RT and UT are effective methods capable of inspecting the full weld cross section. The effectiveness of RT and UT is contingent on the size, shape, and orientation of a discontinuity. RT is effective in recording volumetric discontinuities and is also sensitive to planar discontinuities aligned with the inspecting radiation. UT is very sensitive to planar discontinuities normal to the inspecting sound beam. Both RT and UT are required to ensure detection of discontinuities that may be missed if using only one of the NDT methods. The complementary strengths of each method increase the effectiveness of the testing.

C-12.16.2.2 T- and Corner Joint Tension and Repaired Groove Welds. Radiographic inspection cannot be used effectively to examine T- and corner joints. Physical limitations on film and source placement prevent complete examination of the weld joint. UT does not have these limitations and is capable of inspecting T- and corner joints.

C-12.16.2.3 Fillet Weld Repairs. MT is a method of inspection that complements visual inspection techniques of fillet welds. MT also reveals near-surface discontinuities, but is primarily intended to be a surface inspection. MT inspection of fracture critical fillet weld repairs aids a thorough visual inspection, as well as detecting near-surface discontinuities (see C-8.7.8 for a more detailed explanation about MT).

C-12.16.3 RT Requirements. Verification of RT sensitivity and the acceptability of radiographs is based on the clarity of the Image Quality Indicators (IQIs) on the film. There are two types of IQIs accepted by the code for nonfracture critical welds, the hole-type and the wire IQI. For fracture critical weld radiographs, only the hole-type IQI is allowed. The hole-type indicator provides additional information regarding the RT image, including the presence of angular distortion of the image caused by placement of the source (see 8.10.7).

C-12.16.4 Cooling Times Prior to Inspection. As the joint restraint and strength of steel increases, so does the concern that hydrogen-induced cracking may occur. Restraint will be more severe in welds that are over 50 mm [2 in] thick. Most hydrogen-induced cracks occur within the first 48 hours, even though they have been known to occur much later under some unusual conditions. The waiting periods described in this subclause are considered to be reasonable to ensure that hydrogen-induced cracks have had a chance to form, but are short enough not to interfere unnecessarily with fabrication. Preliminary visual inspection may begin immediately after the completed welds have cooled. RT may be performed immediately following cool-down to detect volumetric discontinuities and early cracks, particularly in the weld metal. UT and MT will detect hydrogen-induced cracking and therefore are subject to this time delay. The final surface visual inspection is performed after the waiting period.

C-12.16.5 Inspection and Record Keeping

C-12.16.5.1 Certified Reports. Detailed records are part of an effective fracture critical welding and fabrication inspection program. Unless otherwise specified, the Contractor is responsible for all NDT records, showing what welds were tested and the results of each test. When critical repairs are employed, a record of the repair and its NDT is maintained.

Fracture critical members or member components should have inspection records for each individual piece, and all documentation developed during the fabrication of the FCM should be made a part of this record. Records include traceability of the material to the specific mill test reports, as provided by the Contractor's materials control system.

C-12.17 Repair Welding

C-12.17.1 WPS Requirements. Repair welding is performed to the requirements of this Fracture Control Plan. This includes performing all welds to an approved WPS. WPSs may be preapproved for repairs classified as noncritical. Repairs classified as critical are to be fully documented by the Contractor, including dimensions, NDT indications and proposed repair methods, and submitted for the Engineer's approval on an individual basis for each repair. WPSs qualified for welding of FCMs need not be requalified for repair welding, provided the joint detail used allows access for welding.

C-12.17.1.1 Approval Procedures. Because the need for repairs tends to be caused by typical discontinuities, such as lack of fusion, slag inclusions, porosity, undersize welds, lack of penetration, cracks, etc., it is acceptable to have preapproval by the Engineer of procedures that describe in detail how the repair is to be performed.

C-12.17.2 Noncritical Repair Welds. There are two classifications for repairs: noncritical and critical. Noncritical repairs, as described in this subclause, usually entail limited difficulty: increasing weld size for undersize welds, removing minor edge gouges, excavations less than 65% of the weld size in depth, repairing undercut, and base metal surface repairs.

C-12.17.2.1 Noncritical Repair Procedures. Because noncritical repairs share a number of common requirements and utilize straight-forward methods for repair, procedures may be developed and preapproved without case-by-case submittals. The procedure includes enough detail to allow the Contractor to make the repairs according to the requirements of this Fracture Control Plan. Subclause 12.17.6 lists the minimum provisions that the procedure is to include. The use of preapproved repair procedures may begin immediately upon verification by the QA Inspector that the procedure covers the intended repair (see 12.17.1.1).

C-12.17.3 Critical Weld Repairs. A critical repair as described in this subclause requires the approval of the Engineer before the repair can begin. Unless designated noncritical in 12.17.2, all FCM repair welding is to be considered critical. Typical critical weld repairs include fabrication errors such as mislocated holes, repair of deep laminar discontinuities, repair of cracks in base metal and weld metal, and repair of discontinuities that require gouging more than 65% of the weld depth. The procedure includes specific detail that will allow the Contractor to make the repairs according to the requirements of this Fracture Control Plan, and documents the location of the discontinuity to be repaired. Subclause 12.17.6 lists the minimum provisions to include in the procedure.

C-12.17.4 Approval. Appropriate repair methods are essential for ensuring the integrity of the final structure, so all critical repairs need to be approved by the Engineer before the repair begins. If a noncritical repair becomes critical due to exceeding expected limits or defects in the initial repair, the Engineer's approval is necessary before proceeding. The procedure gives details of the type of discontinuity, and location and extent of repair. The possibility of cracking from residual stresses and distortion in repairs under high restraint should also be considered.

C-12.17.5 Inspection. All repair welds are to be inspected to the original weld's requirements, verifying the repaired weld is acceptable to the code and FCP. The cooling times before final inspections may be performed as described in 12.16.4 also apply for weld repairs. The Engineer may require additional inspections.

C-12.17.6 Repair Procedure Minimum Provisions. The minimum repair procedure provisions are included in this subclause to provide the Contractor and Engineer with adequate information to ensure a satisfactory repair, and to verify that the procedures are implemented. At a minimum, repair procedures are to include the items described in this subclause, but additional measures may be necessary to ensure acceptable results, especially for nontypical situations (high restraint, joints qualified by test, etc.).

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C-Annex G
Welding Requirements for Conventional, Nonfracture Critical AASHTO M 270M/M 270 (A709/A709M) HPS 485W [HPS 70W] Components with Reduced Preheat and Interpass Temperature

C-G2. Filler Metal Requirements

Research conducted by the HPS Steering Committee and Welding Advisory Group for HPS 485W [HPS 70W] found that reduced preheat using filler metals with a maximum diffusible hydrogen level of 4 mL/100 g were typically required to have a minimum heat input of 40 kJ/in in order to meet the quality requirements of the code. However, some filler metals were capable of producing acceptable quality weldments at lower heat inputs.

A limited number of filler metals were tested based on recommendations of consumable manufacturers. Other SAW filler metals may also produce acceptable quality production welds, and should be allowed to be qualified for welding HPS 485W [HPS 70W] when in conformance with the requirements of Table 7.3. Research conducted at this time has suggested that certain FCAW and GMAW-Metal Core consumables selected from the AWS classifications listed in Table 6.1 may not consistently produce acceptable quality weld metal. The Engineer should thoroughly evaluate other proposed consumables before allowing their use in the work.

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C-Annex H
ESW Consumable Requirements

C-H1.4 The ESW-NG electrode mechanical properties were developed around an electrode chemical composition and the mechanical properties produced in the deposited state of the electrode in PQR test plates. When the electrode classification of the ESW-NG electrode is finalized in AWS A5.25/A5.25M, *Specification for Carbon and Low-Alloy Steel Electrodes and Fluxes for Electroslag Welding*, the classification will be based on the mechanical properties and chemical composition of the ESW-NG electrode of Annex H, containing the identical interim requirements of Annex H and any additional tests that may be required by the filler specification. It may be appropriate to remove the lot testing requirement once the AWS A5.25/A5.25M specification is in place.

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C-Annex J
Advanced Ultrasonic Examination

C-J3.4 E-Scan. Also called an electronic scan.

C-J3.11.1 A-Scan. This is the view by which all other views are formed and is the basis for acceptance or rejection of ultrasonic indications.

C-J3.11.2 C-Scan. Normally the C-scan is uncorrected for angled beam inspections.

C-J3.11.3 Sectorial View. Also called S-scan or sectorial scan. Those terms are not used in this annex because they are also used to refer to a beam movement pattern (see J3.19).

C-J3.11.4 Side View. Sometimes called B-scan or D-scan. These terms are not used in this annex because there is no consensus on which letter corresponds to side view or end view.

C-J3.11.5 End View. Sometimes called B-scan or D-scan. These terms are not used in this annex because there is no consensus on which letter corresponds to side view or end view.

C-J3.12 Line Scan. Also called a linear scan. This term is not used in this annex because "linear scan" is also used to refer to an E-scan (see J3.4).

Certain types of PAUT operational software allow for the configuration of multiple scan types (e.g., S-scan + S-scan, or S-scan + E-scan) to be performed in a single line scan. This technology allows for data collection from multiple search units in a single line scan or from a single search unit but with multiple scan types generated in sequences.

C-J3.16 Multiple piezoelectric elements are sometimes arranged in patterns in a common housing; these are usually linear, matrix, or annular in shape.

C-J3.19 S-Scan. Also called a sector scan, sectorial scan, swept angle scan, or azimuthal scan. See C-J3.11.3 for the use of this term and some of its alternatives to mean a type of imaging view or data display.

C-J3.20 Saturated Signal. Some systems contain enough bit depth to read signal amplitudes above 100% FSH, but even then there is an upper voltage limitation that the system can adequately measure the true amount of voltage returned from the search unit.

C-J3.25 Time Corrected Gain. Also called time varied gain (TVG).

C-J3.26 Virtual Probe Aperture (VPA). Also called active aperture.

C-J3.27 Volume-Corrected Scan. This correction is found to be useful to compensate for surface path distance variations in angle-beam inspections.

C-J5.7.1 Supplemental Calibration Block. Typically the thickness of this block will be a minimum of 2 1/4 times the thickness of the material being examined, when full V-path examinations are done from one face of the joint (i.e., only from Face A as illustrated in Table 8.3). For thicker specimens in which the scan plan details half V-path examinations from multiple faces (i.e., Face A and B as illustrated in Table 8.3), the thickness of the block may be reduced to the material thickness being evaluated (1T). It may be necessary with thicker components to plan for multi-face examinations to reduce calibration block size and to enable easier calibrations. An example of a block including the basic hole size of J5.7 is a Phased Array Calibration Standard (PACS) type block as shown in Figure J.3.

C-J7.1 Scan Plans. The same scan plan may be used for similar weld geometries with similar surrounding component geometries as long as the weld and HAZ are covered.

C-J7.1.1 Caution should be applied when using computer modeling programs for creating scan plan because computation errors are possible, which can lead to inadequate coverage. Due to this, manual plotting should be used to verify scan plan coverage of the initial configuration when computer modeling is used.

C-J7.2.1 Index Positions. The number of index positions required will increase as the material thickness increases. For thinner materials of approximately 6 mm [1/4 in] or less, a single index may supply the proper coverage if the part configuration allows. For material thickness above this, 2 or more index positions are typically required. Ultimately, the adequacy of the number of index positions is determined by the coverage shown in the scan plan and dictated by the ability to meet the coverage requirements of J7.4.

C-J7.2.3 Supplemental E-Scans. E-scans may be useful for welds that can be accessed only from a single side, for welds in T-joints, or other configurations in which complete coverage of the weld, fusion face, or HAZ will be difficult.

C-J7.4 Testing of Welds. For welds in corner or T-joints, the weld may be examined with a straight beam or low-angle longitudinal waves from an appropriate face to aid in obtaining coverage.

C-J7.4.4 Inspection for Transverse Indications. Encoded scanning is possible but not practical with scanning pattern D and not compatible with scanning pattern E. Therefore, encoding is not required for inspection for transverse indications.

C-J8.2.4 Standard Sensitivity Level (SSL). SSL, ARL, and DRL are based on AWS D1.1 Annex O. Annex O rejection level is 5 dB above SSL. 5 dB is a 1.78:1 ratio. 50% (height of SSL) × 1.78 = 89% (height of ARL).

C-J9.3.1 Scanning Gain. Additional scanning gain when TCG is applied is intended to aide in detection for manual examinations. Most phased array equipment or evaluation software has the capabilities to increase gain (or similar with color palette adjustments) to serve the same purpose of aiding in detection of discontinuities. Additionally, gain settings greater than 6dB above SSL would produce saturated signals that would interfere with relevant signals for acceptance.

C-J9.3.3 Scanning Speed. Exceeding the indicated scanning speed can cause data dropout.

C-J10.2 Acceptance Criteria. Characterizing defects as cracks is done by assessing the location of the indication, signal rise-fall time, pulse duration, echo dynamic patterns, and amplitude. If cracks are suspected but cannot be confidently characterized, alternate NDT methods should be used to help classify the indication. There are various resources and training available for defect characterization. One such resource is the ASME *Boiler and Pressure Vessel Code*, Section V, Nonmandatory Appendix P, "Phased Array (PAUT) Interpretation." Annex O of AWS D1.1 has diagrams that are useful for understanding these criteria.

C-J11.2 Data Analysis and Recording Requirements. Post-acquisition data analysis will result in numerous evaluative actions and manipulations intended to characterize indication responses from benign geometries and metallurgical responses. This process, by its nature, will require modification to ensure complete and systematic disposition of the examination record.

C-J13.1 Reporting. For particularly long retention requirements, measures may need to be taken so that the data remains readable (not only that the storage medium is intact but that there is software to read it).

C-J14.2(1) The probe adjustment may be performed with an angle-beam or 0° technique. The two signals may be obtained by using a block with multiple side drilled holes located close in proximity, multiple signals from radius as in a standard IIW/DSC block, or multiple thicknesses such as the DS block shown in Figure 8.6. The probe is then manipulated to the optimum position over the reflectors to obtain a 2:1 signal ratio. Once the 2:1 ratio is established, the probe will remain in that position and gain adjustments are made to set the indications at the specified amplitude.

(2) The gain shall be increased using the receiver gain adjustment to obtain 100% of full screen height of the larger response. The height of the lower response is recorded at this gain setting as a percentage of full screen height.

(3) The height of the higher response shall be reduced in 10% steps to 10% of full screen height and record the height of the second response for each step.

(4) The larger signal shall be returned to 80% to ensure that the smaller signal has not drifted from its original 40% level due to coupling variation. Repeat the test if variation of the second signal is greater than 41% or less than 39% full screen height.

(5) For an acceptable tolerance, the responses from the two reflectors shall bear a 2 to 1 relationship to within ±3% of full screen height throughout the range 10% to 100 % (99% if 100% is saturation) of full screen height.

(6) The results shall be recorded on an instrument linearity form as shown in Table J.4.

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List of AWS Documents on Structural Welding

Designation	Title
D1.1/D1.1M	*Structural Welding Code—Steel*
D1.2/D1.2M	*Structural Welding Code—Aluminum*
D1.3/D1.3M	*Structural Welding Code—Sheet Steel*
D1.4/D1.4M	*Structural Welding Code—Reinforcing Steel*
D1.5M/D1.5	*Bridge Welding Code*
D1.6/D1.6M	*Structural Welding Code—Stainless Steel*
D1.7/D1.7M	*Guide for Strengthening and Repairing Existing Structures*
D1.8/D1.8M	*Structural Welding Code—Seismic Supplement*
D1.9/D1.9M	*Structural Welding Code—Titanium*

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