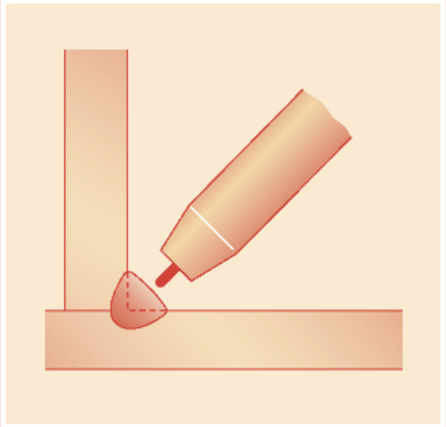
WOODHEAD PUBLISHING IN MATERIALS



MIG welding guide

Edited by Klas Weman and Gunnar Lindén

CRC

WP

MIG welding guide

Related titles:

New developments in advanced welding
(ISBN-13: 978-1-85573-970-3; ISBN-10: 1-85573-970-4)
Recent developments in high-technology areas have significantly transformed the welding industry. Automation, computers, process control, sophisticated scientific instruments and advanced processing methods are all common in the modern industry. Today's engineers and technologists have to support complex systems and apply sophisticated welding technologies. This comprehensive new book discusses the changes in advanced welding technologies preparing the reader for the modern industry.

Processes and mechanisms of welding residual stress and distortion
(ISBN-13: 978-1-85573-771-6; ISBN-10: 1-85573-771-X)
Measurement techniques for characterisation of residual stress and distortion have improved significantly. More importantly the development and application of computational welding mechanics have been remarkable. Through the collaboration of experts, this book provides a comprehensive treatment of the subject. It develops theoretical treatments on heat transfer, solid mechanics and materials behaviour that are essential for understanding and determining welding residual stress and distortion. It outlines the approach for computational analysis that engineers with sufficient background can follow and apply. The book will be useful for advanced analysis of the subject and provides examples and practical solutions for welding engineers.

Cumulative damage of welded joints
(ISBN-13: 978-1-85573-938-3; ISBN-10: 1-85573-938-0)
Fatigue is a mechanism of failure that involves the formation of cracks under the action of different stresses. To avoid fatigue it is essential to recognise at the design stage that the loading is such that fatigue may be a possibility and to design the structure with inherent fatigue strength. However, fatigue strength is not a constant material property. It may be assessed by fracture mechanics, but such characteristics are based on quantitative analysis and mere assumption. This book is primarily concerned with fatigue under variable amplitude loading, unlike most tests performed under constant loads.

Details of these and other Woodhead Publishing materials books and journals, as well as materials books from Maney Publishing, can be obtained by:

- visiting our web site at www.woodheadpublishing.com
- contacting Customer Services (e-mail: sales@woodhead-publishing.com; fax: +44 (0) 1223 893694; tel.: +44 (0) 1223 891358 ext. 30; address: Woodhead Publishing Limited, Abington Hall, Abington, Cambridge CB1 6AH, England)

If you would like to receive information on forthcoming titles, please send your address details to: Francis Dodds (address, tel. and fax as above; email: francisd@woodhead-publishing.com). Please confirm which subject areas you are interested in.

Maney currently publishes 16 peer-reviewed materials science and engineering journals. For further information visit www.maney.co.uk/journals.

MIG welding guide

Edited by
Klas Weman and Gunnar Lindén

Woodhead Publishing and Maney Publishing
on behalf of
The Institute of Materials, Minerals & Mining

CRC Press
Boca Raton Boston New York Washington, DC

WOODHEAD PUBLISHING LIMITED
Cambridge England

Woodhead Publishing Limited and Maney Publishing Limited on behalf of
The Institute of Materials, Minerals & Mining

Published by Woodhead Publishing Limited, Abington Hall, Abington,
Cambridge CB1 6AH, England
www.woodheadpublishing.com

Published in North America by CRC Press LLC, 6000 Broken Sound Parkway, NW,
Suite 300, Boca Raton, FL 33487, USA

First published 2006, Woodhead Publishing Limited and CRC Press LLC

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library.

Library of Congress Cataloging in Publication Data
A catalog record for this book is available from the Library of Congress.

Woodhead Publishing Limited ISBN-13: 978-1-85573-947-5 (book)
Woodhead Publishing Limited ISBN-10: 1-85573-947-X (book)
Woodhead Publishing Limited ISBN-13: 978-1-84569-147-9 (e-book)
Woodhead Publishing Limited ISBN-10: 1-84569-147-4 (e-book)
CRC Press ISBN-10: 0-8493-9112-1
CRC Press order number: WP9112

The publishers' policy is to use permanent paper from mills that operate a sustainable forestry policy, and which has been manufactured from pulp which is processed using acid-free and elementary chlorine-free practices. Furthermore, the publishers ensure that the text paper and cover board used have met acceptable environmental accreditation standards.

Project managed by Macfarlane Production Services, Dunstable, Bedfordshire
(macfarl@aol.com)
Typeset by Godiva Publishing Services Ltd, Coventry, West Midlands
Printed by TJ International Limited, Padstow, Cornwall, England

Contents

Part I Technologies

Part II Quality and safety issues

Part III Applications

Contributor contact details

(* = main contact)

Editors
Professor K. Weman
WEMAB AB
Gårdsjögatan 11
S-696 32 Askersund
Sweden

E-mail: klasw@wemab.se

Professor Gunnar Lindén
Klarinettvägen 115
S-434 47 Kungsbacka
Sweden

E-mail:
gunnar.linden@airliquide.com

Chapters 1, 2, 6, 10
Professor K. Weman
WEMAB AB
Gårdsjögatan 11
S-696 32 Askersund
Sweden

E-mail: klasw@wemab.se

Chapters 3, 7, 11, 13, 14
Professor Gunnar Lindén
Klarinettvägen 115
S-434 47 Kungsbacka
Sweden

E-mail:
gunnar.linden@airliquide.com

Chapters 4, 5
Lars-Erik Stridh
ESAB AB
Box 8004
S-402 77 Göteborg
Sweden

Email: larserik.stridh@esab.se

Chapter 8
Joakim Hedegård
Corrosion & Metals Research Institute
Drottning Kristinas v. 48
S-114 28 Stockholm
Sweden

Email: joakim.hedegard@kimab.se

Chapter 9
Peter Nerman
Corrosion & Metals Research Institute
Drottning Kristinas v. 48
S-114 28 Stockholm
Sweden

Email: peter.nerman@kimab.com

Chapter 12
Tony Nilsson
SSAB Tunnplåt AB
S-781 84 Borlänge
Sweden

Email: tony.nilsson@ssab.com

Anders Skirfors
SSAB Oxelösund AB
S-613 80 Oxelösund
Sweden

Email: anders.skirfors@ssabox.com

Chapter 15
Dick Skarin, Johan Nilsson and David Green
ABB Automation Technology Products AB
S-695 82 Laxå
Sweden

E-mail: dick.skarin@se.abb.com
johan.t.nilsson@se.abb.com
david.green@se.abb.com

Chapters 16 and 17
Ragnar Gudmundson
Gatebergsvägen 30
S-439 92 Onsala
Sweden

E-mail: ragnar.g.welding@telia.com

Chapter 18
Hans Broström
Volvo Wheel Loaders AB
Box 303
S-671 27 Arvika
Sweden

E-mail: hans.brostrom@volvo.com

1

The MIG welding process

K WEMAN, Wemab AB, Sweden

1.1 Introduction

Gas metal arc welding (GMAW) also called MIG (metal inert gas) if the shielding gas is inert, for example argon, or MAG (metal active gas) if the gas has a content of an active gas such as CO_2. In Europe the process is usually called MIG/MAG or just MIG welding.

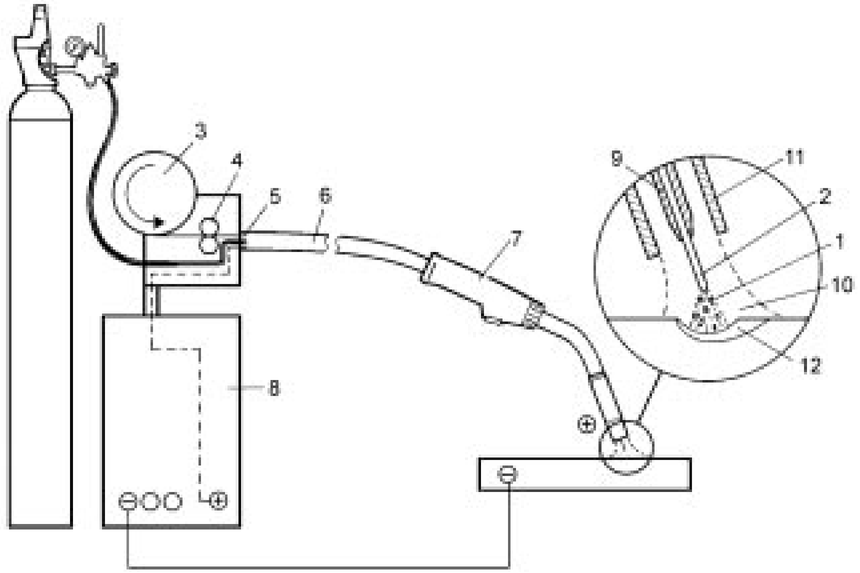
The process is used in a wide range of plate thicknesses even though it has been most dominant in thin sheet welding. This is because of its easiness in starting and stopping and thereby its relatively high productivity. Compared to stick electrode (MMA) welding there is no need for the frequent electrode changes and slag removal.

The principle of MIG welding is that a metallic wire is fed through the welding gun and melted in an arc. The wire serves the dual purpose of acting as the current-carrying electrode and as the weld metal filler wire. Electrical energy for the arc is supplied by a welding power source. The arc and the pool of molten material are protected by a shielding gas, which is either inert or active. In this context, an inert gas is one that does not react with the molten material. Examples of gases in this category are argon and helium. Active gases, on the other hand, participate in the processes in the arc and the molten material. Argon containing a small proportion of carbon dioxide or oxygen is an example of an active gas.

In order to achieve optimum welding performance, it is important that the welding parameters are set correctly. Examples of such parameters in MIG welding are voltage, wire feed speed and the shielding gas flow.

1.1.1 Process principles

Figure 1.1 shows the principle of MIG welding. The arc is struck between the workpiece and a wire that is continually fed forward to replace the metal that is melted away. The wire is supplied on a reel or drum, and is fed to the welding gun by drive rollers, which push the wire through a flexible conduit in the hose



1.1 The principle of MIG welding. 1. Electric arc. 2. Electrode. 3. Reel or drum. 4. Drive rollers. 5. Flexible conduit. 6. Hose package. 7. Welding gun. 8. Power source. 9. Contact tip. 10. Shielding gas. 11. Shielding gas nozzle. 12. Weld pool.

package to the gun. Electrical energy for the arc is supplied by a welding power source. The welding current is passed to the electrode through a contact tip in the welding gun. This contact tip is normally connected to the positive pole of the power source, and the workpiece to the negative pole. Striking the arc completes the circuit.

The small diameter wire, typically around 1 mm, is fed by the wire feeder with a speed of several metres per minute. Arc length is then self-adjusted depending on the voltage setting of the constant potential power source.

A shielding gas that protects the electrode, the arc and the weld pool from the effects of the surrounding air, flows through the shielding gas nozzle that surrounds the contact tip. This shielding gas may be either inert, which means that it is inactive and does not participate in the processes occurring in the weld pool, or active.

As the filler wire is fed through automatically while the welding gun is moved over the workpiece manually, MIG welding is usually referred to as being a semi-automatic method. However, the method lends itself easily to automation by mechanising the movements of the welding gun or arranging for the workpiece to move.

Robot welding has been a common way of welding automation, as the robot can easily be reprogrammed to fit new objects. The robot makes the welding movement in combination with the manipulator for the workpiece. The robot control system incorporates the setting of all welding data, search of starting point, seam tracking and the possibility of superimposing a weaving pattern to the welding motion. Robot welding is explained in Chapters 15 and 16.

Advantages, limitations and applications

Among the benefits of MIG welding, the most important are probably the high productivity and the relatively low heat input to the workpiece, combined with the fact that the method is so easy to automate. Productivity is considerably higher than with manual metal arc welding, as there is no need to interrupt welding to replace filler rods, and little or no slag chipping is required.

MIG welding is a particularly flexible method and covers a wide range of applications:

- Plate thicknesses from 0.5 mm and upwards. The low heat input is valuable when welding thin sheet, in helping to avoid deformation and distortion of the sheet. When welding in thicker metal, the filler passes can be applied with high productivity.
- All commonly encountered structural materials, such as mild, low-alloy and stainless steel, aluminium and its alloys, and several other non-ferrous metals.
- Surface coated metals, e.g. Zn-coated steel.
- In all welding positions.

These advantages have enabled the MIG method to find many applications, both in large-scale industry and in smaller, jobbing workshops. Examples of industries in which the method is common include the automotive, shipbuilding, construction and offshore industries.

The MIG method can be said to be both easy and difficult to learn and use. If pretensions extend no further than to weld together two pieces of sheet metal without any special demands in terms of the quality of the finished weld, then the method can be said to be easy to use. On the other hand, if there are special requirements, such as through welding, complete fusion, few pores, etc., then the MIG process requires considerable skill and experience on the part of the welder.

A limitation of the MIG method compared to MMA is that the welding equipment is more complex and therefore more expensive and less portable. It also has a more limited application outdoors, as the shielding gas must be protected from draughts. The design of the welding gun, too, means that accessibility may be poorer in certain welding situations.

1.2 The welding arc

A welding arc is an electric discharge between two electrodes. The welding current is conducted from the electrode to the workpiece through a heated and ionised gas, called plasma. The voltage drop and current in the arc give the amount of electric power that is released, the heat of which melts the electrode and the joint faces.

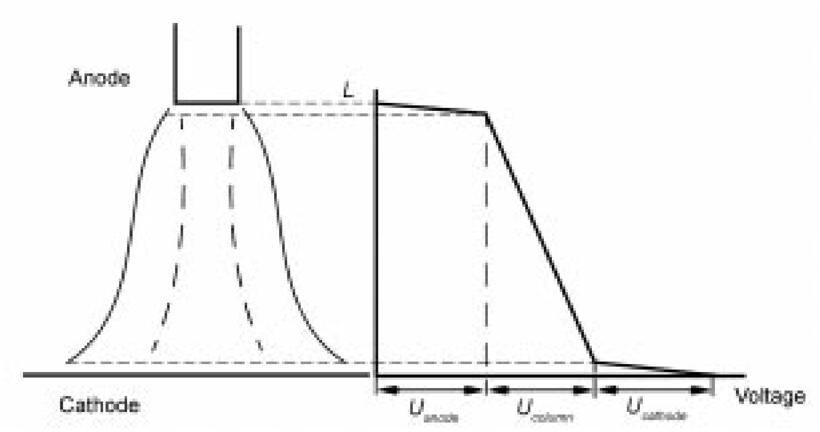
The power developed must also be high enough to keep the temperature of the arc sufficient for the continued transport of the current. The temperature maintains ionisation of the gas, i.e. it creates electrically charged particles that carry the current.

Depending on the choice of shielding gas, different temperatures are needed to keep the plasma ionised. Argon, for example, is easier to ionise than helium. That means that welding in helium or helium-mixed gases produces a higher voltage drop and higher heat input to the weld pool.

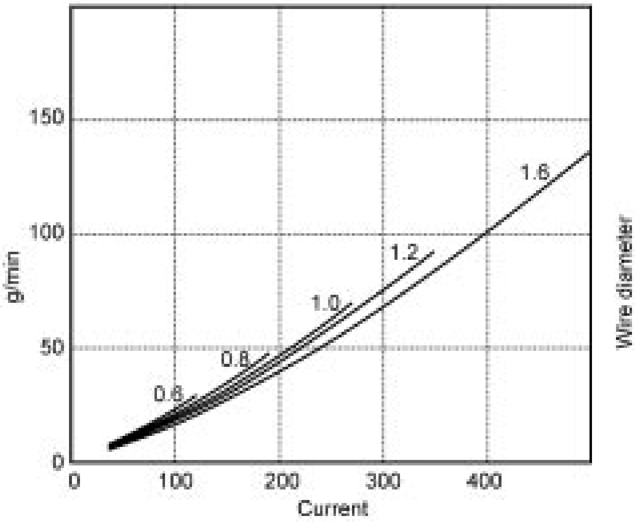
When welding with a consumable electrode, such as MIG welding, the arc has two main functions. One is the above-mentioned supply of heat for melting the materials; the other is the transport of the molten electrode material down to the weld pool. This droplet transfer is very dependent on the electromagnetic forces and surface tension in the arc region. These forces have a great influence on the behaviour of the welding process, and enable one to distinguish between different arc types.

1.2.1 Heat generation

In the arc heat losses by heat conduction appear close to the surface of the wire electrode and the workpiece. These anode and cathode regions of the arc have therefore considerable voltage drops (see Fig. 1.2), and in spite of their small size, more than half of the total voltage drop is here. Thermal balance is achieved because the heat that is conducted into the electrode and the joint is replaced by electric energy.



1.2 The voltage distribution in the arc.



1.3 Deposition rate for some wire diameters (solid wire, ESAB Autrod 12.51).

The arc can be divided into the anode region, cathode region and the arc column. Normally the wire electrode is the anode, the positive polarity and workpiece the cathode, the negative polarity.

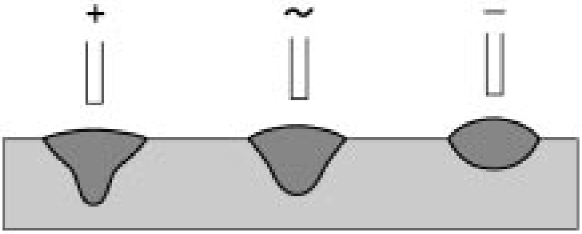
Heat generated in the anode region melts the wire and heats the melted drop. In the same way, heat generated in the cathode area will heat and melt joint faces.

As the anode voltage can be considered as a constant voltage drop, the heating effect is proportional to the current. The melting rate is thereby also proportional to current and, at least in theory, independent of voltage setting. Figure 1.3 shows the deposition rate as a function of welding current. The deviation from a straight line depends on the resistive heating of the wire stick-out, that part is proportional to the square of the current.

Polarity

MIG welding is normally used with DC current and the electrode connected to positive polarity. Negative polarity is seldom used because of the bad arc stability.

The heat generation is higher at the anode than the cathode. The reason for this is that the input of electron emission energy at the cathode is retrieved at the anode. In spite of that, most penetration is achieved and the deposition rate is lower when the wire electrode is positive (see Fig. 1.4). The explanation is that some of the heat developed at the anode will over-heat the drops of melted wire material rather than melt the wire. The high-temperature drops transfer heat



1.4 The effect of wire polarity on penetration.

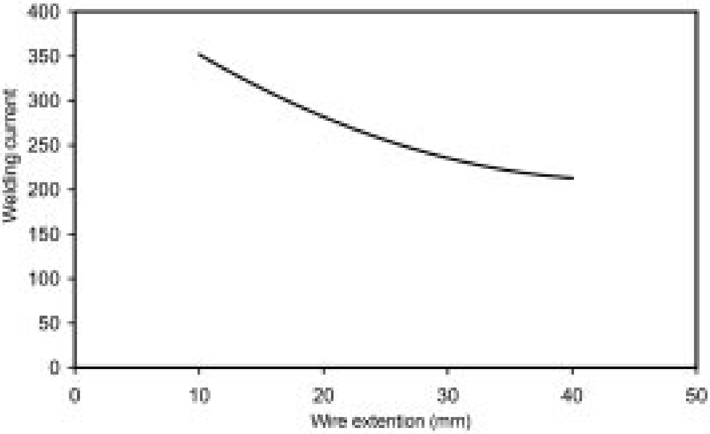
energy to the pool. As welding with the positive electrode gives the most stable arc and most suitable welding result, it is the natural polarity for MIG welding. In some special cases, AC or DC negative polarity is used.

Penetration

The depth of penetration depends of different factors. Heat input and also energy density are important. The angle of filler wire to the joint, and polarity are other variables that influence penetration.

Influence of wire stick-out

Depending on the stick-out length (the wire extension, see Fig. 1.16, page 21) the resistive losses will pre-heat the wire. The current needed to melt the wire is then reduced and the arc will automatically adapt itself to this lower current (see Fig. 1.5). An unintentional increase of the stick-out length will reduce heat input to joint and increase the risk of weld defects.



1.5 Welding current decreases if wire stick-out length is increased.

Generation of welding fumes

As a result of the intense heating from the arc, some metal is vapourised from the electrode material. When this vapour leaves the arc it is oxidised and forms the welding fume. If some other material is present, that has lower vaporising temperature, fume generation will increase. Examples of such substances are the flux in a flux-cored wire or oil, paint or zinc coating on the workpiece.

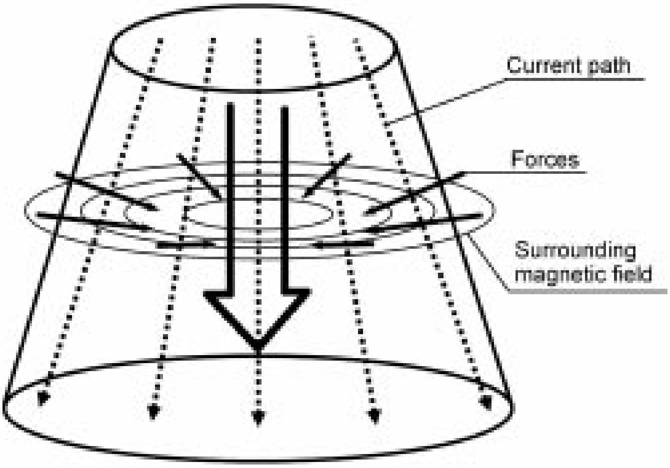
1.2.2 Forces acting on the arc and metal droplets

The release of melted drops from the wire depends mainly on electromagnetic forces and the surface tension. Other forces acting on the drops are gravity and the drag force from the plasma jet.

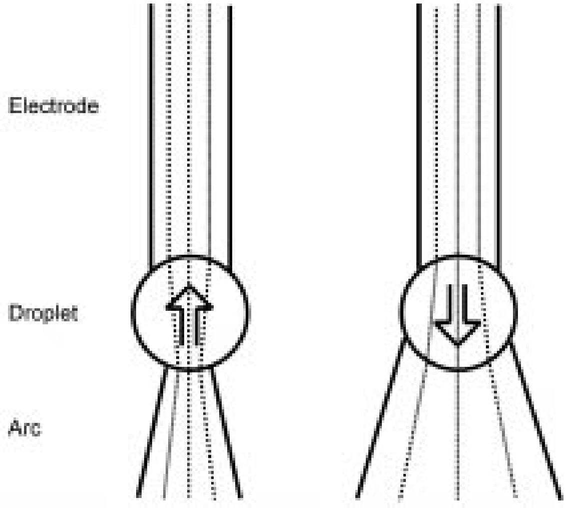
The magnetic forces appear as a result of the combination of the currents and magnetic field that exists in the arc region. The forces are both perpendicular to the current path direction and the magnetic field direction. As the arc often has a conical shape (see Fig. 1.6), the resulting magnetic force will be directed downwards. This force accelerates the arc plasma and produces a plasma jet.

The electro-magnetic forces also act in a similar way on the melted drops (see Fig. 1.7). The resulting direction depends, however, on the width of the arc.

- If the diameter of the arc is less than the the wire size, the magnetic forces are directed upwards and counteract the release of the drop.
- If the arc diameter is larger than the wire, the drop release is improved by the downward direction of the magnetic forces.



1.6 The resulting magnetic force acting on the arc is directed downwards.

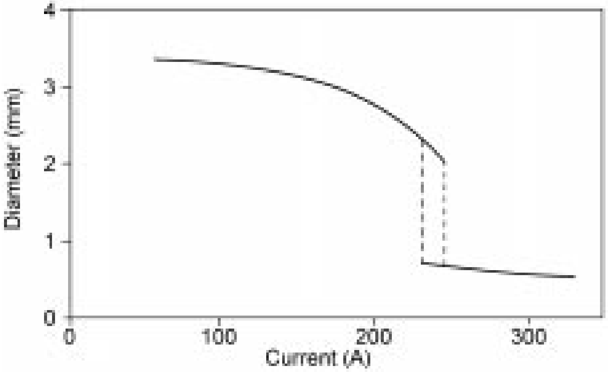


1.7 The magnetic force acting on the droplet may be either upwards or downwards depending on arc size in relation to wire diameter.

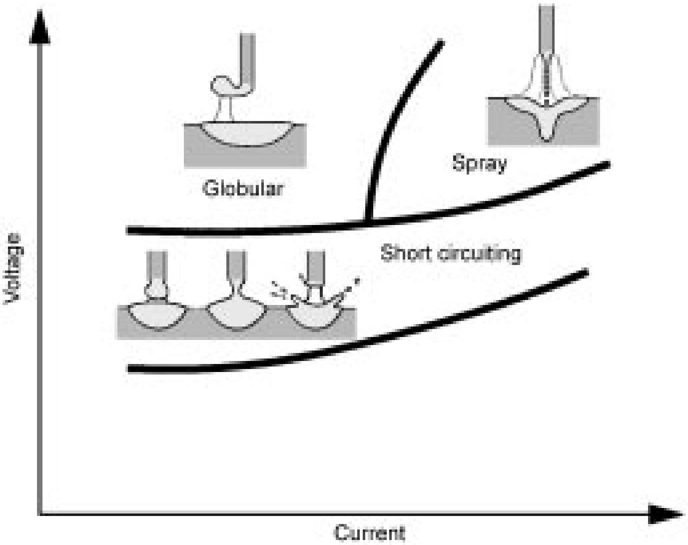
The arc diameter depends on welding current and shielding gas composition. High current and argon-rich gas mixture will contribute to the creation of small drops. At a certain transition current the drop diameter suddenly changes from big to small drops (see Fig. 1.8). The transition current varies if the diameter of the welding wire is changed. A smaller wire diameter tends to decrease the level of the transition current.

1.3 Metal transfer

The stability of a DC arc with a consumable electrode (i.e. a filler wire) depends largely on how the molten metal is transferred in the arc. One can distinguish



1.8 Drop diameter as a function of the welding current.



1.9 Arc types for different current and voltage conditions.

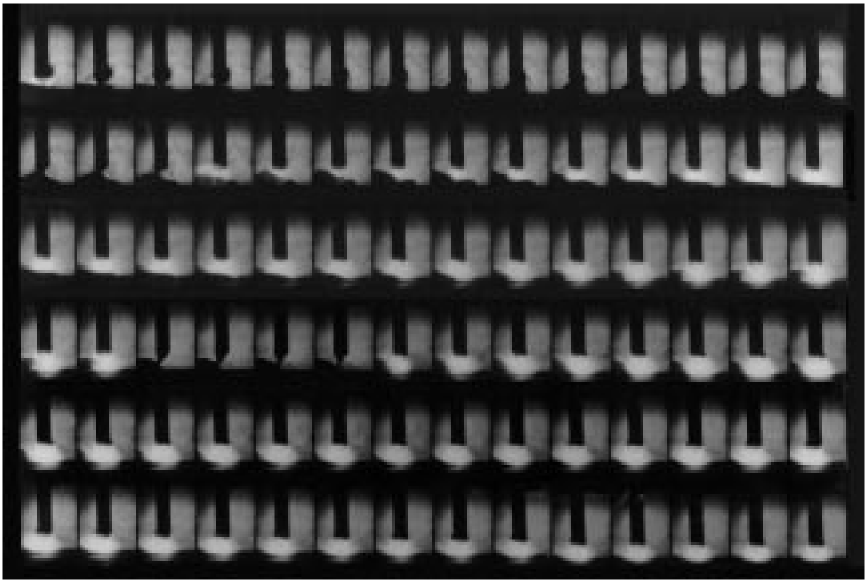
essentially between two different types of arc, depending on the material transport: the short arc (short-circuiting arc) and the spray arc. The type of metal transfer depends upon the voltage and current settings (see Fig. 1.9), but also on other parameters such as the shielding gas composition and wire diameter.

1.3.1 Short arc welding

Short arc welding (or dip transfer) is normally used in the lower current range for sheet metal in all positions. The heat input from short arc welding is low, which makes the process suitable for welding thinner materials.

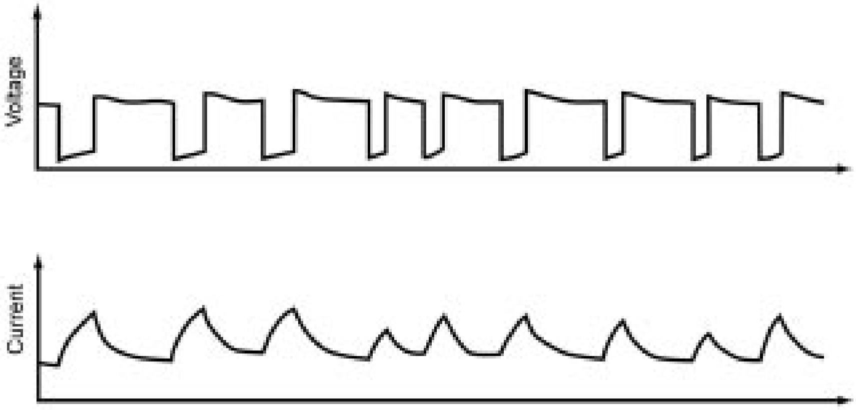
At low current the magnetic forces are small and are directed upwards. The droplet hanging at the tip of the electrode tends to increase in size and the process runs the risk of being unstable. A way to overcome this problem is to keep the arc length (see definition in Fig. 1.16) so short that the droplets will dip into the pool before they have grown too much. Surface tension will then start the transfer of the melted material and the tail of the droplet will be constricted by the magnetic forces, the so-called ‘pinch effect’. Figure 1.10 shows a sequence from a high-speed film. Notice the short arc length; about the same size as electrode diameter (0.8 mm). No metal is transferred in the form of free droplets across the arc gap.

Short circuit frequency is normally in the range of 50–200 Hz. The stability of the short circuiting transfer is very sensitive to variations in the shielding gas, the chemical composition of the electrode and the properties of the power source and wire feeding system. If the short-circuit current is too high, it has a



1.10 High-speed film of short circuiting arc welding. The whole sequence represents 7 ms of welding. Two short circuits appear. The second short circuit is an occasional touch without any metal transfer.

considerable effect on the pinch-off forces, causing weld spatter. Some means of limiting the short-circuit current must therefore be provided in the power unit, e.g. through the use of an inductor coil. Figure 1.11 shows a transient sequence of the voltage and current. When the drop short-circuits the arc, the voltage drops to a low value and the current starts to rise. Typically the arc is short-circuited at about 25% of the time during short arc welding.



1.11 Arc voltage and current sequence during short arc welding.

It is not always easy to optimise short-arc welding to achieve a completely stable arc. A simple way to judge if the welding is going well is by the noise of the arc. The objective is to achieve a consistent, high short-circuiting frequency, resulting in small droplets being transferred to the workpiece and spatter droplets being so fine that they do not adhere to the workpiece.

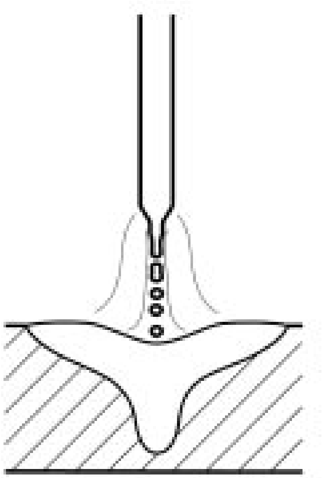
Ignition of the arc can also be sensitive, and it is important in this respect that all parts of the equipment should be in good condition in order to avoid irritating chattering when striking the arc.

1.3.2 Spray arc welding

Spray arc welding can only be used at high current, above the transition current, and high voltages (see Fig. 1.9). Arc stability is very good and metal is transferred in a stream of small droplets (see Fig. 1.12). Heat input and deposition rate is high and welding is therefore limited to the horizontal position and material over 5 mm thick.

Above the transition current, the resulting magnetic forces helps the droplet to be released from the surface tension at the electrode. As there are no short circuits, the arc is stable and spatter-free. It should be noted that a pure spray arc cannot be obtained when using CO_2 as the shielding gas: the shielding gas must be pure argon or (preferably) with a small proportion of CO_2 (not more than 25%) or a few percent of O_2. Spray arc welding is particularly suitable for MIG welding of aluminium and stainless steel, for which the shielding gas is mainly argon.

With a thin filler wire, it is possible to perform successful spray arc welding at lower currents than with a thicker filler wire.



1.12 Drop transfer in spray arc welding.

The arc voltage should be set at such a value that it is just sufficiently high to maintain a short-circuit-free arc. The filler wire is normally connected to the positive pole. The current must normally be above 200–250 A.

1.3.3 Globular transfer

At currents lower than needed for spray transfer and with voltage above the pure short arc welding there is a mixed region characterised with droplets larger than the electrode diameter and often with an irregular shape. The molten drop grows until it detaches by short-circuiting or by gravity. The globular transfer mode is most often avoided.

1.3.4 Pulsed MIG welding

Pulsed MIG welding is used mainly for welding aluminium and stainless steel, although it may also be used for welding ordinary carbon steel. The method requires a power source with ability to produce suitable pulses (30–300 Hz) that controls the transfer of the droplets. This makes it possible to extend the spray arc range down to low welding data and provides a stable and spatter-free arc as a welcome alternative to short arc welding.

The stable and controlled drop transfer with pulsed arc allows the use of an increased electrode diameter. This is often utilised in aluminium welding where the electrode is difficult to feed because of its softness.

Pulsed welding restricts the choice of shielding gases. As for spray arc welding, the CO_2 concentration in an Ar/CO_2 mixture must not be too high. Common 80/20 mixed gas, as used for short arc welding, represents a limit value.

For further information about pulsed MIG welding, see Chapter 6.

1.4 Magnetic arc blow

The force or ‘arc blow’ that arises when the magnetic field around the arc is not completely symmetrical, is a well-known problem with arc welding. In critical cases, it can result in a defective weld.

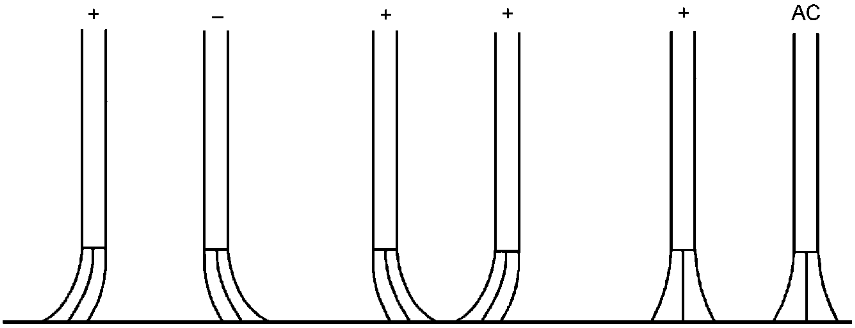
- The weld pool, and thus the weld bead, can be deflected towards one side, producing a defective weld.
- If the arc is deflected along the joint, the width of the bead and the penetration can be affected.
- The protection provided by molten slag or gas can be affected, resulting in the formation of pores.
- The problem becomes worse, and more noticeable, as the welding current increases, as this results in a corresponding rapid increase in all the electromagnetic forces in and around the arc.

1.4.1 Possible causes

- Welding close to a return current connection, or with an asymmetrically connected connection, is a common cause of this problem.
- The magnetic arc blow that arises when welding close to an edge or where the metal thickness increases.
- Electrodes close to each other when using multi-electrode welding. Each current-carrying conductor is surrounded by its own magnetic field. The magnetic field from one electrode can interfere with the arc from an adjacent electrode (see Fig. 1.13).
- Induced magnetic fields from the welding current. When welding in steel, the workpiece can provide a path for the magnetic field. An example of this occurs in connection with internal longitudinal welding of a pipe or tube, where the welding current supply cable induces a magnetic flux in the tube.
- Permanent magnetic fields. These are magnetic fields from magnetic clamping bedplates, or remanence (residual magnetisation) in the workpiece from, for example, lifting magnets, magnetic non-destructive testing or parts of jigs that have become magnetised by the welding current.

1.4.2 Recommended measures

- Do not connect the return current connector close to the position of the weld. Welding towards the return current connection is often preferable. When welding long items, the current can be more evenly distributed by attaching equally long return current cables to each end of the object.
- The use of adequately sized starting and finishing strips can reduce problems at the beginning and the end of a joint.



1.13 Effect from a nearby electrode. If one of the wires has AC current the arc-blow effect is reduced.

1.5 Process control

The process has the ability to operate stably also without any electronic control. If the wire speed is kept constant and the power source is of a constant voltage type, the arc length will remain stable. This is because of the self-adjusting feature of the arc. If some disturbance happens that changes the arc length, the voltage drop over the arc is changed and the resulting current reaction from the power source influences the rate at which wire is melting such that the arc length will be stabilised again. This behaviour is described in more detail in Chapter 2.

The high short-circuit current of the power source is an advantage at the start of welding, when the wire hits the workpiece. Normally, a stable arc is maintained within a tenth of a second. To achieve an almost perfect start, methods are developed where the wire is re-tracked after first contact and the arc is initiated from a controlled low-current pilot arc. This is similar to the lift-arc start method sometimes used in TIG-welding.

1.5.1 Control by welding current

With short arc welding the high short-circuit current needs to be limited to avoid too much spatter. This is traditionally done with an inductor coil, often with different output terminals on the power source to allow the user to optimise process stability. More advanced power sources use electronic or digital control to adjust current amplitude and process stability.

1.5.2 Wire feed speed control

The wire feed speed is normally kept constant during welding but new methods actively use the wire feed speed to control the process. Gerd Huismann (1999) describes a ‘Controlled Short-Circuiting MIG’ process where wire speed is the main control parameter. Instead of using high short-circuiting current normally used in short arc welding, the bridge of liquid metal is instead broken by lifting the wire. Improved process stability could be obtained.

The principle is further developed by Fronius. Their process called CMT (Cold Metal Transfer) is spatter-free, has a low heat input and is well suited for the welding of thin sheets or MIG brazing.

1.6 Consumables

MIG welding is used for mild steel, low alloyed and stainless steel, for aluminium, copper and copper alloys, nickel and nickel alloys, etc. Plate thicknesses down to 0.5 mm can be welded. There is no technical limitation upwards, but the risk for lack of fusion at low heat input or oversized pool will increase. The filler material often has a chemical composition that is similar to the base material.

1.6.1 Solid wire

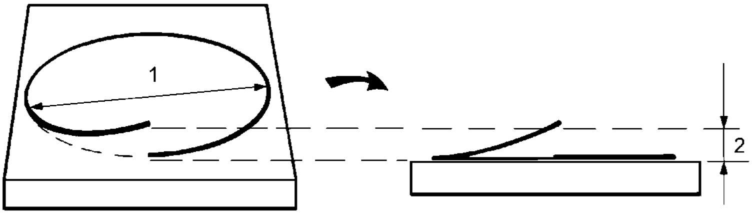
The electrodes for MIG welding are available in the 0.6–2.4 mm range for use with many different materials. Wires are normally supplied on reels and wound to ensure that the wire does not snag when being withdrawn. Important factors are that it must be clean with a smooth finish to feed easily and be free from metal flaws. Best feeding performance is achieved with wires coated with a thin layer of copper. One important condition is that the copper is well fixed to the wire, if not, it will clog up the wire conduit and prevent smooth feeding of the wire. If maximum reliability is required, as, for example, at advanced robot welding, copper-free wire may be an alternative.

To get the right performance of the arc, it is necessary for the current to be transferred to the electrode close to the opening of the contact tip. To improve the contact force and to define the contact point the electrode is somewhat curved, i.e. it has a radius of 400–1200 mm (see Fig. 1.14). The electrode is normally delivered on 10–15 kg coils (steel) but for large consumption a container of about 200 kg can be ordered.

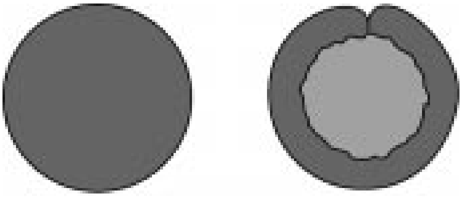
1.6.2 Cored wire

One can distinguish between solid wires and cored wires. The latter type consists of a metallic outer sheath, filled with flux or metal powder, as shown in Fig. 1.15. The flux cored wires can have either a rutile or basic filling (see Chapter 5 for further details). They can also be self-shielded for use without shielding gas. The weight share of MIG weld metal deposited from cored wires in 2002 was 24% in the USA, 34% in Japan but only 10% in Europe.

The cost per unit of cored wire is considerably higher than that of solid wires, but they are in some respects superior to solid wire. Cored wires are mainly used for somewhat thicker plates. High deposition rate and good side-wall penetration characterise cored wire.



1.14 Checking cast diameter (1) and helix size (2).



1.15 Cross-section of solid and cored wire.

There are today two main types of cored wires:

- Wires that require the use of shielding gas, usually CO_2 or Ar/CO_2 mixture.
- Wires that do not require additional shielding gas, known as self-shielded flux cored wires.

When carrying out cored wire welding without a shielding gas (self-shielding), the same power source and wire feed unit are usually used as would be used for welding with shielding gas. However, the welding torch can be simpler, as there is no need for a gas supply.

Fumes are a problem when welding with high current, not least when using self-shielded flux cored wires. One solution to this problem is to use a welding torch with an integrated fume extraction.

The *metal powder-filled cored wires* contain a powder that consists mainly of iron and alloying elements. The only slag formed is in the form of small islands of silicon oxide. These wires have a high productivity in the horizontal position.

Flux-cored wires are best suited for positional welding, as the slag provides better control of the weld pool. In comparison with solid wires, cored wires are also regarded as producing somewhat less risk of poor fusion.

Self-shielded flux cored wires are filled with a powder that develops gases to protect the weld pool. This is done by means of appropriate additives which are gasified in the arc. The resulting substantial expansion excludes the surrounding air from the arc and weld pool.

1.7 Shielding gases

A shielding gas is used to prevent the molten metal from the harmful effects of the air. Even small amounts of oxygen in the air will oxidise the alloying elements and create slag inclusions. Nitrogen is solved in the hot melted material but when it solidifies the solubility decreases and the evaporating gas will form pores. Nitrogen can also be a cause of brittleness. The shielding gas also influences the welding properties and has great importance for the penetration and weld bead geometry. The most common components of shielding gases are presented here, for more detailed information of the choice of gas for different purposes, see Chapter 3.

Argon (Ar)

Argon is one of the most popular shielding gases thanks to its suitable properties. As an inert gas, it has no chemical interaction with other materials. Therefore it is suitable for materials such as aluminium and stainless steel. At MIG welding of mild steel an addition of CO_2 or a small amount of oxygen will increase the welding properties, especially for short arc welding. Contents of up to 20% CO_2 improves the penetration (limits the risk of lack of fusion) while 5–8% will give reduced spatter.

Helium (He)

Helium, like argon, is an inert gas. It gives more heat input to the joint. Mixed with argon it increases welding speed and is advantageous for the penetration in thick-walled aluminium or copper where it compensates for the high heat conduction. Drawbacks with helium are the high cost and the low density.

Carbon dioxide (CO_2)

Pure carbon dioxide can be used for short arc welding. It is a cheap gas, it has good properties for welding of galvanised steel and gives better safety against lack of fusion than argon-based gases. Drawbacks are a higher amount of spatter and the fact that the gas cannot be used for spray arc welding.

Hydrogen (H_2)

Small additions of hydrogen can be used to increase heat input and welding speed in the same manner as helium, but it is much cheaper. Because of the risk of cracks, hydrogen can only be used for welding of austenitic stainless steel. It actively reduces the oxides and is therefore also used in root gases.

Oxygen (O_2)

Oxygen is also used as a small addition to stabilise the arc in MIG welding.

Nitrogen (N_2)

Nitrogen can be used as an alloying element in ferritic-austenitic stainless steels. A small additive of nitrogen in the shielding gas compensates for the losses when welding.

1.8 Welding parameters

The MIG welding process is dependent on a number of welding parameters:

- Wire size.
- Voltage.
- Wire feed speed and current.
- Welding speed.
- Inductance or dynamic properties.
- Wire stick-out.
- Choice of shielding gas and gas flow rate.
- Torch and joint position.
- Torch weaving patterns.
- Pulsed wire feed.

Most of these parameters must be matched to each other for optimum welding performance. The working point must be within the working range or tolerance box for the particular welding situation. The time needed for the adjustment at a typical welding situation is normally short for an experienced welder but the optimisation of a weld for an automated production line may need some effort.

1.8.1 Wire size

The size of wire is chosen according to welding current, but in opposition to stick electrodes each wire has a large and overlapping range of current. As a rule, the material transfer is smother with a thinner wire. When welding with soft aluminium wire, the risk of feeding problems can be reduced with a thicker wire.

1.8.2 Welding voltage

Increased voltage increases the arc length and gives a wider weld bead. Undercut is a sign of too high a voltage. If short arc welding is used, a higher voltage reduces the short circuit frequency, which will give larger drops and more spatter.

Too low a voltage, on the other hand, will increase the risk for stubbing and bad start performance.

On thin plates short arc welding gives the possibility of high welding speed without burn-through. Normally the voltage here is adjusted to a low setting but only where the short circuit frequency is still high and the arc stability good.

Fillet welds that are exposed for fatigue loads need to have a low profile weld bead with smooth edges. That is optimised by the correct choice of welding voltage. The same is valid for multilayer welds where too high a bead profile may result in lack of fusion for the subsequent weldments.

1.8.3 Wire feed speed and current

Current is set indirectly by the wire feed speed and diameter. Current is the main parameter for welding and has to be chosen to plate thickness and welding speed with respect to the weld quality.

1.8.4 Welding speed

From a productive point of view, it is of interest to use maximum welding speed. A general tendency is that a higher speed produces a more narrow weld and at an excessively high speed the tolerance for all parameter variations will decrease.

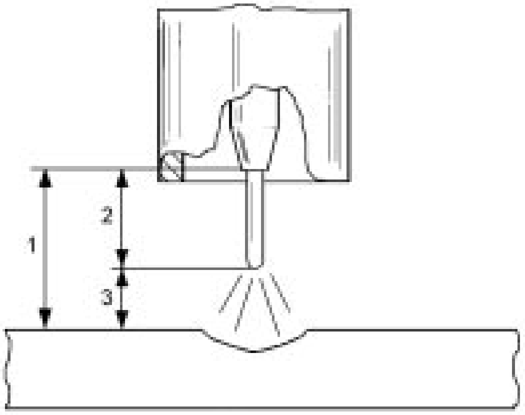
By using special techniques, it has been shown to be possible to open up the tolerance box further and allow higher welding speed and deposition rate, see Chapter 8.

1.8.5 Inductance

It is often possible to adjust the inductance of the power source to fit the wire size to give the right welding properties. The most sensitive is short arc welding. A low value gives a distinct and concentrated arc but the spatter will increase. A higher value gives a somewhat wider bead and a softer sound. Too high an inductance gives bad stability with a tendency for stubbing. Inductance may more or less be replaced by a greater drooping characteristic of the power source. In inverter power sources the dynamic properties of the power source are normally managed by digital or electronic control circuits.

1.8.6 Wire stick-out length

Easiest to measure is the contact tip distance from the joint surface (see Fig. 1.16). A rule of thumb says that a normal distance is 10–15× diameter of the wire. Too small stick-out increases the risk of burn-back, where the arc will weld the electrode together with the contact tip. Too long a distance to the workpiece will increase the risk for stubbing, especially at the start.



1.16 Definitions of contact tip-to-work distance (1), wire extension (2) and arc length (3).

The contact tip-to-work distance also has an influence on the current and penetration profile. If the stick-out (wire extension) is increased, the current and heat input decreases while the amount of deposited metal remains. This reduces the penetration and gives exessive weld metal, and if it was unintentional, a risk for lack of fusion appears. A good rule is therefore to keep the wire stick-out constant during the welding operation. If used in a controlled way the wire extension can be used to increase deposition rate. The risk for burn-through at high welding data is also reduced.

1.8.7 Choice of shielding gas

Mixtures of argon with 5–20% carbon dioxide (CO_2) are most popular in the welding of mild and low alloyed steels. For spray and pulsed arc welding, a low content of CO_2 can be an advantage. Pure CO_2 is an alternative for short arc welding that gives good penetration and safety against lack of fusion but increases the amount of spatter.

For *stainless steels* argon is also used but with only small additions of CO_2 or oxygen (O_2).

For welding of *aluminium, copper and copper alloys* normally pure argon or argon helium mixtures are used. Helium increases the heat input, which will compensate for the large heat conduction in thick-walled aluminium or copper.

1.8.8 Gas flow rate

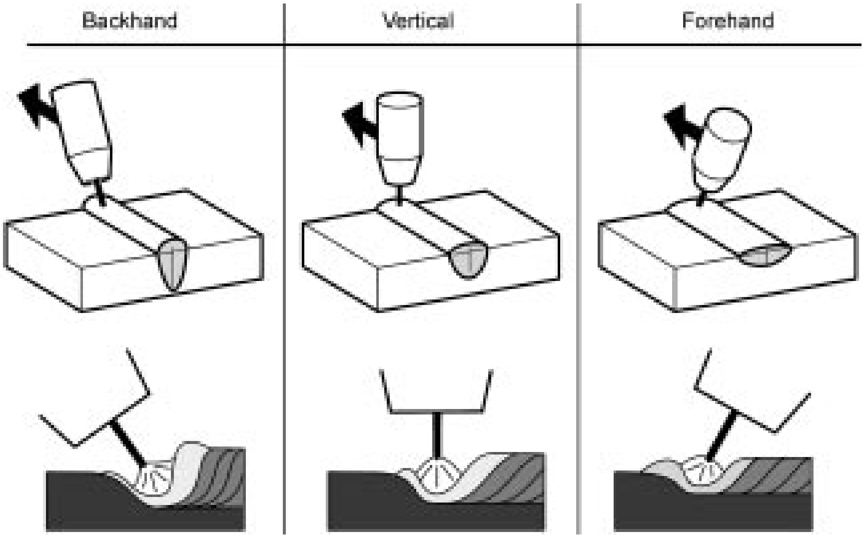
The gas flow must be adapted to the arc. At low current 10 litres per minute can be sufficient while at higher welding data up to 20 litres can be required. Welding in aluminium needs more gas than steel does.

1.8.9 Torch and joint position

Angles of the torch relative to the joint are also an important welding parameter. If directed away from the finished part of the weld (*forehand technique*), it will make the penetration profile more shallow and the width of the seam wider (see Fig. 1.17). Forehand technique can also be used to attain higher welding speed. On the other hand, if the torch is directed towards the finished part of the weld (*backhand technique*), the penetration will be deeper and the seam width narrower.

Angles of the torch in a section across the welding direction have influence on the risk for lack of fusion (see Fig. 1.18).

The electrode on such thick plates is often positioned 1–2 mm offset on the base plate. That will compensate for the higher heat dissipation and give a symmetrical penetration profile. If the plate to be welded is not totally horizontal but has an inclined joint, it also affects the weld contour and penetration profile.

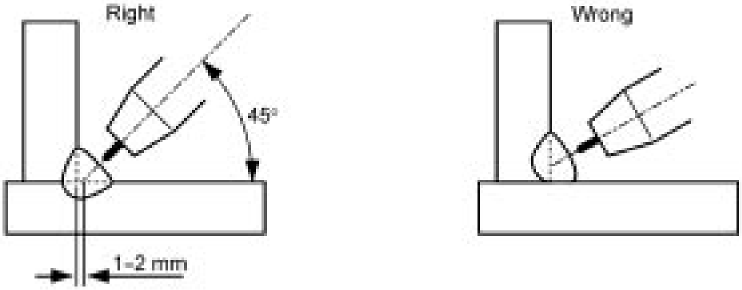


1.17 Effect of electrode position and welding technique.

By welding downhill, the weld reinforcement can be lower and the welding speed will usually be increased. At the same time, the penetration is lower and weld bead wider. This is beneficial for welding sheet metal. Uphill welding causes the weld pool to flow back and form a high and narrow weld.

To reduce the risk of lack of fusion it is important to prevent the melted metal flowing too much before the arc. This can be the case when welding with high heat input, a large pool and welding with too much forehand or in the downhill position.

Contact tip-to-work distance (see Fig. 1.16) should be kept constant when welding.



1.18 Gun angle across the welding direction at fillet welding.

1.8.10 Torch weaving patterns

A weaving motion is sometimes used to bridge gaps or widen a last pass in a multilayer weld. Weave techniques are also often used in a vertical position to improve control of the weld pool. The motion can be made from side-to-side, sometimes in combination with a back-and-forth motion and eventually also with a pause at each side.

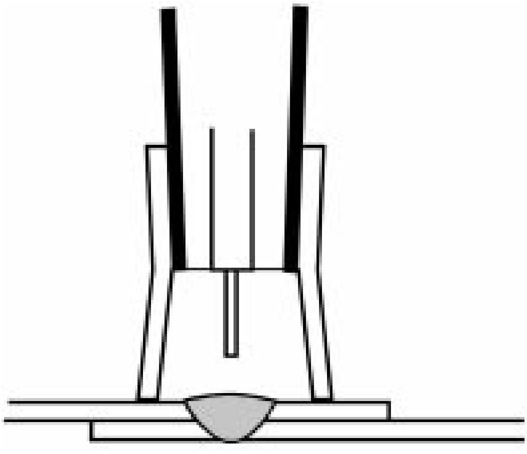
1.8.11 Pulsed wire feed

Pulsed wire feed speed at low frequency allows metal partly to solidify between the pulses. During the high current pulse time penetration and gap bridging is secured but mean welding data can be low enough to allow positional welding. Similar advantages as for torch weaving can be achieved. The pattern generated in weld bead is the same as for pulsed TIG welding.

1.9 Arc spot welding

This is a MIG method intended to produce spot welds. The welding torch has a gas nozzle with support legs (see Fig. 1.19), and the welding time is controlled by a timer. The joint is often of an overlap type as normally used in resistance spot welding. However, in this case, the workpiece does not need to be accessible from both sides. The support legs provide the correct wire stickout, and also serve to some extent to press the two pieces of metal into contact with each other.

Welding data (voltage and wire feed) are considerably higher than is usual for the particular metal thickness concerned. The welding time is controlled to



1.19 Arc spot welding.

produce a through-weld within a relatively short time, generally less than one second. This produces a low convexity with good coverage, without the need to make a hole in the upper piece of metal.

In comparison with continuous welding, the process has the following advantages:

- Less heating and distortion.
- Very simple to operate: simply position and press the trigger.
- Lower, better-shaped convexity, particularly when welding thin sheet.
- Plate thickness up to 6 mm can be welded without any joint preparation.

As the welding process is short but intensive, the method is less sensitive to welding position, imbalance in the metal thicknesses, gap width variations, etc., and can therefore be used when such effects would otherwise make it difficult to produce successful continuous welds.

1.10 High productive methods

Besides MIG welding with normal solid wire, cored wire has been used as a way to improve welding productivity and deposition rate. When robot welding became popular during the 1970s the productivity was increased mainly by the increased arc time factor. The welding process was often the same as was earlier used for manual welding. In the 1990s improved methods were introduced, developed specially for mechanised welding. The first improvement was for single wire and later double wire was also used. The most advanced equipment today uses the laser-hybrid process, a combination of laser and MIG welding. The high productive methods are described completely in Chapter 8.

1.10.1 Single-wire methods

The productivity of mechanised MIG welding, using conventional solid filler wires, has constantly improved in recent years. A prolonged resistive heating means that the wire stick-out is preheated, thus permitting a higher rate of feed without a corresponding increase in the current.

The higher wire feed speed results in a high productivity: in some cases, at a rate of up to 20 kg/h of deposited weld metal. Linear welding speed can be twice that of conventional MIG welding, while producing the same appearance of the weld bead and penetration profile. Different types of arc are used: perhaps the commonest is a type of forced short arc that is used within the range covered by conventional welding equipment.

Under certain conditions, a rotating arc is produced when welding at higher welding data. The high productivity, in combination with a high current and large weld pool, mean that welding must be carried out in the most favourable horizontal position.

1.10.2 Tandem and twin wire welding

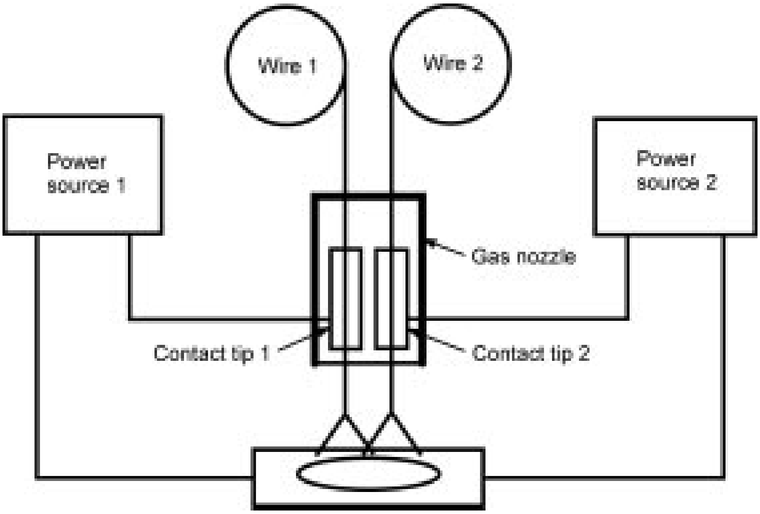
Another way of improving the productivity and raising the welding speed is to use double filler wires. Both wires can be connected to the same power unit, which means that they share a common arc. This method goes under the name of ‘twin arc’. Alternatively, two power sources are used, the method is referred to as ‘tandem welding’ (see Fig. 1.20). Nevertheless, the two wires are so close to each other they weld into a common weld pool.

Welding with two wires can increase the speed to at least twice the normal value or, when welding thin sheet, even higher. In some applications, linear welding speed can be up to 6 m/min.

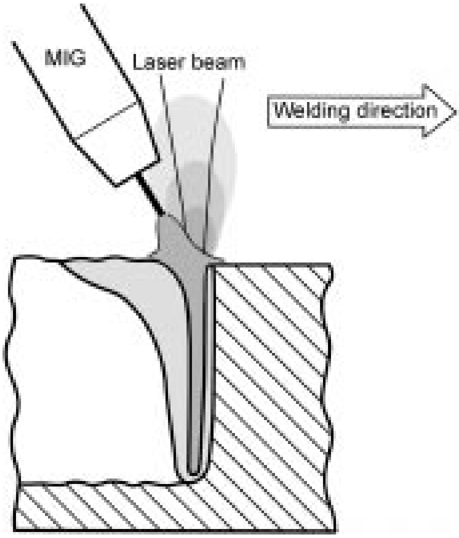
Setting the welding current and voltage can be more complicated when two wires are used, particularly with tandem welding when it is necessary to set the welding data separately for each wire. As the two arcs are close to each other, they can sometimes interfere through magnetic arc blow effect. Therefore this process often uses pulsed welding, with the pulses on each wire displaced out of phase with each other.

1.10.3 Laser/MIG hybrid welding

Hybrid welding refers to a combination of two welding methods, usually laser welding and an arc welding method such as MIG or plasma welding. By combining a laser with MIG welding (see Fig. 1.21), the MIG wire provides molten material that fills the joint. This reduces the requirements for exact positioning and gap tolerances that would otherwise be required for laser



1.20 Tandem MIG welding uses two electrodes, normally positioned one after the other. Each electrode is separately connected to a power source.



1.21 The principle of laser-MIG hybrid welding.

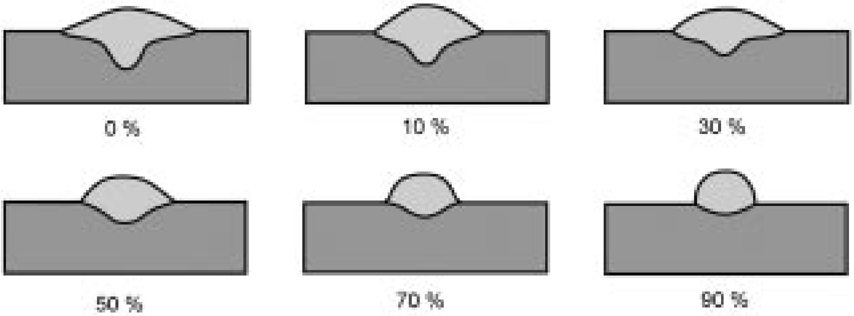
welding alone. In addition, when welding fillet joints, this combination provides reinforcement of the joint.

This also reduces the risk of undercutting, which can easily occur with laser welding, and which unfortunately seriously reduces fatigue strength. However, compared to ordinary MIG welding, the welding speed will be considerably higher due to the laser.

1.11 AC MIG welding

AC MIG welding is not very common, it is mostly used in Japan but was not commercially available in Europe before the end of the 1990s. This type of equipment is used for short arc and pulsed arc welding of details for vehicles in a lower current range up to 200 A.

Negative polarity on the electrode means lower heat input and higher deposition rate. For the AC MIG welding, special power sources are used that produce a square-wave AC current. The fast zero-crossing is necessary to secure re-ignition of the arc. A balance control allows the user to adjust the ratio of negative to positive polarity. In practice that gives the user a tool to change proportion between heat and amount of filler material (see Fig. 1.22). At 50% of negative polarity, only 40% of the current is needed to melt the wire compared to welding with normal positive polarity. The advantage is that thinner material can be welded and it is possible to allow more variations of the gap width. Heat input and deformations decrease.



1.22 Penetration profile at AC MIG welding when the balance control is used to change the ratio of negative polarity from 0–90%.

1.12 Bibliography

ESAB and AGA (1999) *Facts about MIG/MAG welding*. ESAB Welding Equipment AB.

Himmelbauer, K (2005) *The CMT-process – A revolution in welding technology*. Fronius International GmbH.

Houldcroft, P and John, R (1988) *Welding and cutting*, Cambridge, Woodhead-Faulkner.

Huismann, G (1999) *Introduction of a new MIG process, advantages and possibilities.* IIW Doc. 212-952-99. Universität der Bundeswehr Hamburg, Laboratorium für Werkstoffkunde und Schweißtechnik, Hamburg, Germany.

Ponomarev, V and Slivinsky, A (2003) *Welding arc and MIG/MAG welding transfer*, Kiev.

Weman, K (2003) *Welding processes handbook*, Cambridge, Woodhead.

2

Equipment for MIG welding

K WEMAN, Wemab AB, Sweden

2.1 Power sources

The main purpose of the power source is to supply the system with suitable electric power. Furthermore, the power source performance is of vital importance for the welding process; the ignition of the arc, the stability of the transfer of the melted electrode material and for the amount of spatter that will be generated. For this purpose it is important that the static and dynamic characteristics of the power source are optimised for the particular welding process.

2.1.1 Static characteristics

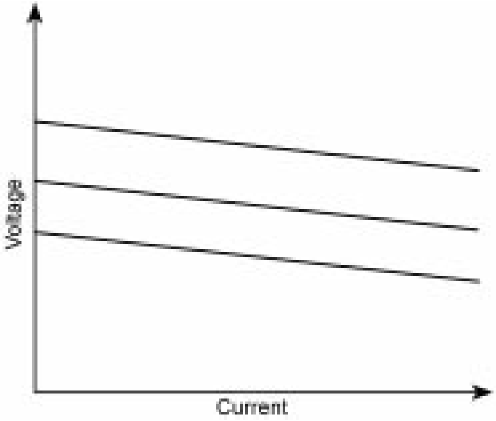
The static characteristics of a power unit can be plotted by loading the power unit with an adjustable resistive load. Normally a constant voltage characteristic is used for MIG welding (see Fig. 2.1).

If the voltage remains almost constant when it is loaded, it is known as a constant voltage or flat characteristic. Typically a voltage drop of 2–5 V/100 A is normal. A straight characteristic maintains good control of the arc length when welding with methods involving a continuously fed filler wire, such as MIG or perhaps submerged arc welding. In this case, the current is determined by the speed of the filler wire (i.e. the quantity of filler material being fed into the weld).

2.1.2 Self-regulation of the arc

The point of intersection between the arc characteristic and the power unit load characteristic is referred to as the working point. The working point at any particular time represents the welding current and voltage at that time. If the arc length is to be stable, the power source characteristic must not slope too much.

If, for example, something happens so that the length of the arc is reduced, the voltage drops and the current increases. It can be seen from Fig. 2.2 that the current increases from working point 1 to working point 2, if the slope of the

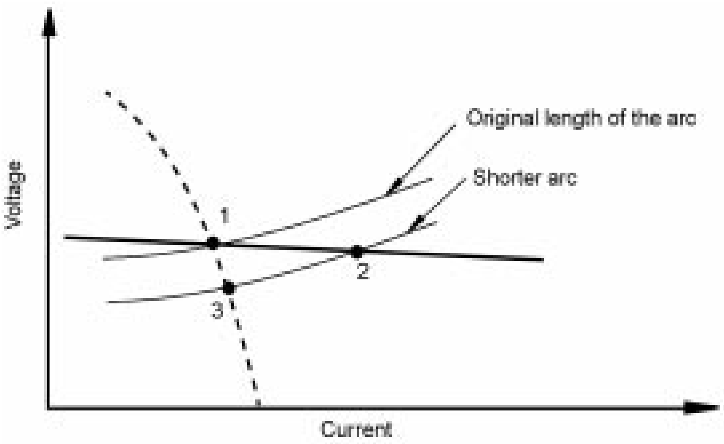


2.1 Example of a constant voltage (straight) characteristic.

characteristic is slight, but only to working point 3 if the characteristic has a steep slope. The increase in current raises the rate of melting of the electrode, and the arc length is restored. This is known as the self-regulation characteristic of the arc length. MIG power units have a straight characteristic in order to provide good self-regulation performance.

2.1.3 Setting the current and voltage

When welding with coated electrodes, or when performing TIG welding, it is the current that is set on the power unit, with the arc voltage then depending on the arc length that is used.



2.2 How the slope of the power unit characteristic affects the welding current if the arc length is altered.

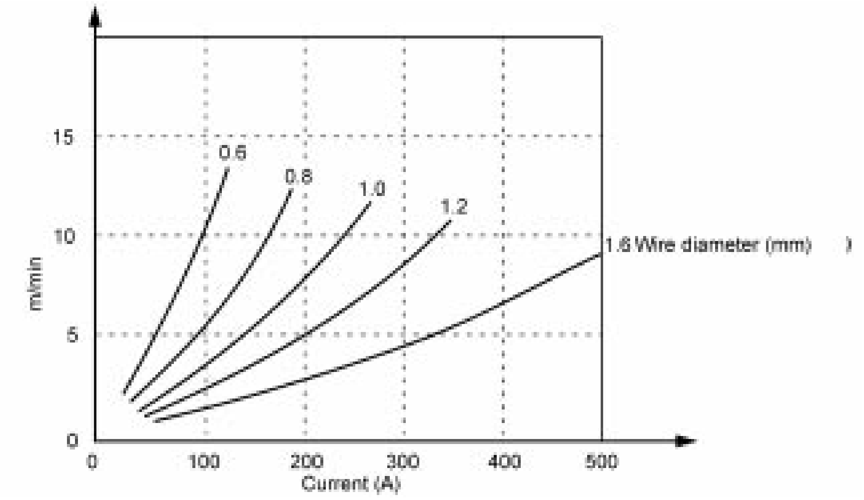
When welding with a continuously supplied filler wire, e.g. MIG welding, it is the voltage that is set on the power unit. The voltage then determines the length of the arc. This is a result of the arc's self-regulation characteristic: if the welder raises the welding torch, the arc length does not alter: instead, it is the wire stick-out that alters. The current cannot be set directly: instead, it depends on the wire feed speed (and wire diameter) used (see Fig. 2.3).

The current, in other words, sets itself so that it is at just the value needed to melt the filler wire at the same rate as the wire is fed out. Changing the voltage, for example, does not greatly affect the current.

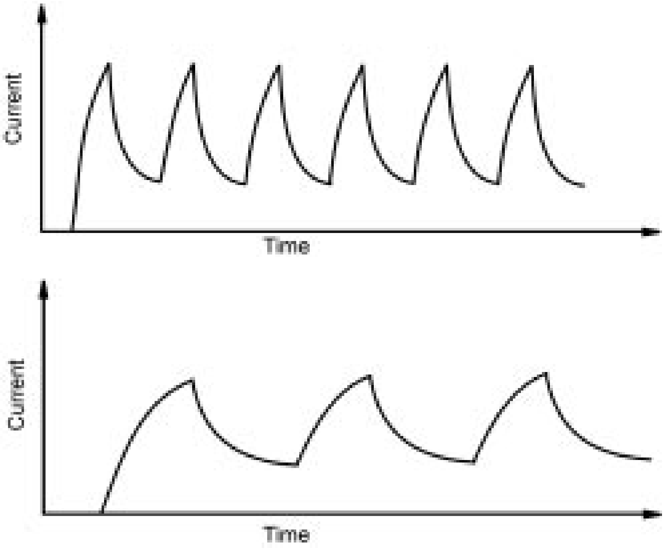
2.1.4 Dynamic characteristic

With relatively slow changes in the arc, one can assume that the working point follows the power unit static characteristic. However, in the case of more rapid changes, the dynamic characteristics of the power unit (mainly its inductance) increasingly determine how quickly the current will change. This is important, particularly when welding with short-circuiting drop transfer.

Power units for short arc welding usually incorporate an inductor in their output. The action of the inductor can be likened to the effect of a flywheel in a mechanical system. If the voltage changes instantaneously, as when a droplet of molten metal short circuits the arc, the current will rise rather more slowly. It is important that there should not be too high a current peak during the short circuit, as this would result in high electromagnetic forces that would cause spatter (see Figs 2.4 and 2.5).



2.3 The relationship between current and wire feed speed for MIG welding with normal stick-out. (Solid filler wire: ESAB Autrod 12.51).

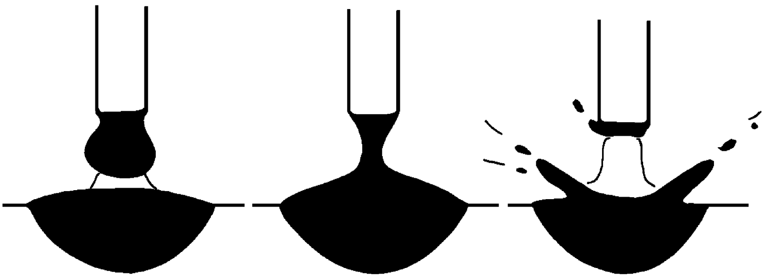


2.4 Welding current in short arc welding with low inductance (top) and with high inductance (bottom).

The aim is to achieve a high, steady short-circuiting frequency, with finely distributed droplets. The arc should strike quickly and cleanly. All this means that the power unit must have the correct dynamic performance.

2.1.5 Welding with alternating current

Special power units for AC welding, with a square wave current, have been developed. They are electronically controlled, and can have such rapid zero-crossing transitions that they can be used for processes that would otherwise require a DC power source, e.g. TIG or MIG welding. An additional function on



2.5 Short-circuiting drop transfer when inductance is low results in increased amount of spatter when the short circuit breaks.

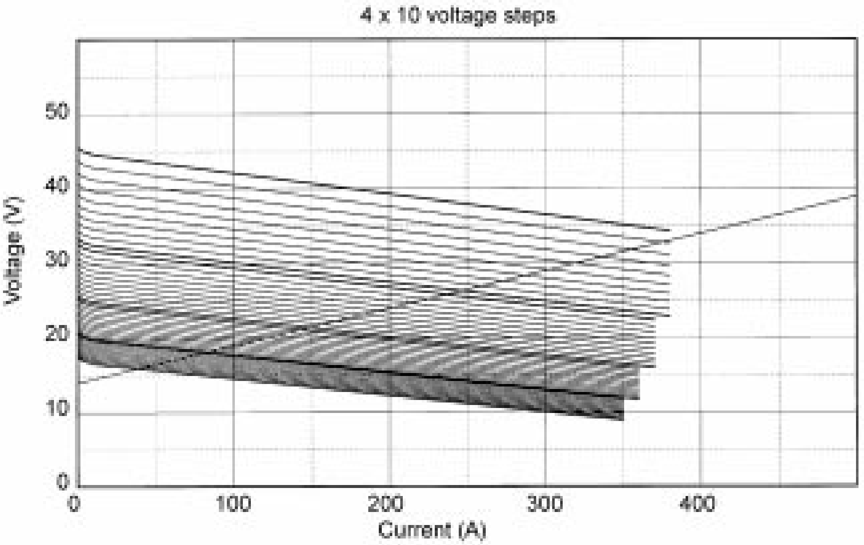
these power units is that it is possible to control the relative proportions of the power supply during the positive and negative parts of the cycle, known as balance control.

2.2 Different types of welding power units

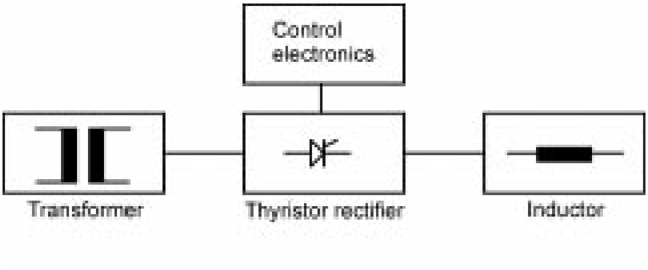
The welding power unit converts the high voltage of the mains supply to a non-hazardous level, i.e. provides means of controlling the current or voltage and produces the necessary static and dynamic characteristics as required by the welding process.

2.2.1 Welding rectifier

A traditional welding rectifier power source produces DC, and usually consists of a large 3-phase transformer with a rectifier on the secondary side. Power sources having a straight characteristic (see Fig. 2.6), for use with MIG welding, generally arrange for voltage control by means of a tap-changer on the transformer. An alternative is to use a thyristor-controlled rectifier bridge (see Fig. 2.7). Unfortunately, this has the drawback of chopping the output voltage, which makes it also necessary to fit a smoothing inductor. This is because the current ripple otherwise would have a considerable effect on the welding characteristics. Thyristor control also provides a means of stepless remote control and insensitivity to variations in the mains supply voltage. Overall efficiency is 70–80%.



2.6 Voltage characteristic for a welding rectifier. It is adjustable in voltage steps, small enough to allow the user to find a suitable welding voltage.



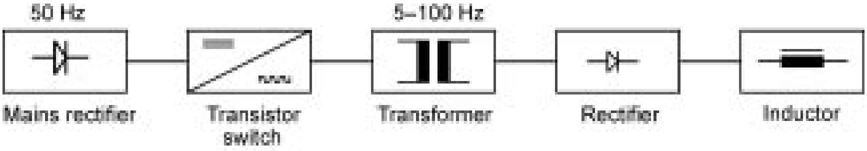
2.7 A thyristor rectifier can be used for stepless control of the welding voltage.

The response speed of the thyristors is limited by the mains frequency but is, nevertheless, sufficiently fast to allow the static characteristics of the power unit to be controlled. This means that the characteristic can be given varying slopes, from straight to drooping, so that the unit can be used with several different welding methods.

2.2.2 Welding inverters

Inverter units appeared on the market during the second half of the 1970s. In a primary-switched inverter unit, the 50 Hz mains supply is first rectified and then, using power semiconductors, is turned back into AC at a higher frequency, usually in the range 5–100 kHz (see Fig. 2.8). The increased frequency makes it possible to decrease the number of turns and the cross-sectional core area size of the transformer and inductor. This reduces the weight of the transformer and inductor to a fraction of what is needed for a 50 Hz unit, making the power unit small and portable. Low losses result in high efficiency, to the order of 80–90%. The high working frequency also allows the unit to be controlled at a speed that is comparable with the rapid processes occurring in connection with droplet transfer in the arc. Such units can therefore have excellent performance. In comparison with traditional power sources, inverter units offer the following advantages:

- Low weight and small size.
- Good welding performance.



2.8 The principle of a welding inverter.

- Several welding processes can be used with the same power source. The fast control necessary for pulsed MIG welding can be achieved.
- High efficiency.

An inverter power source therefore combines low weight with good control arrangements. Its drawbacks are: that it has a more complicated design and is difficult to make adjustable for different mains supply voltages.

The reduced losses save energy consumption. If the efficiency of a 500 A/ 40 V power source is improved by 10% by using an inverter, the saving is 2 kW. By reducing the ambient temperature it also improves the welding environment.

2.3 Development trends

Modern electronics and computer technology have had a considerable effect on the development of arc welding equipment. This applies not only to the power circuits, but also to the control electronics in the power unit and in other parts of the electrical equipment used for welding. This rapid rate of development may seem confusing, providing many new potential setting instruments and controls. The following pages provide a review of the new opportunities and concepts that are available.

2.3.1 Welding characteristics

Where welding characteristics were previously determined by the design and limitations of the heavy current circuits, control can now be provided by electronics and/or computers. Effectively, the high-speed power circuit operates as an amplifier, providing new opportunities not only for control of the welding parameters, but also for control of the process itself.

Electronic control increases the flexibility of the power source, and it is relatively simple to incorporate features enabling it to be used with several different welding methods. In addition to MIG, a power source may, perhaps, also be suitable for use with stick electrodes or TIG welding, without necessarily involving any significant extra cost.

Conventionally designed welding power sources were generally optimised for a particular range of electrodes, materials and shielding gases. The fast reactions of the electronically controlled power sources make it possible to adjust the characteristics to suit the particular process.

Good characteristics are particularly important when using short-arc welding, especially when considering the stream of molten droplets to be transferred to the weld pool. Detachment of each droplet is critical, bearing in mind possible spatter formation and bad welding stability. Correct control can maintain a high, consistent short-circuit frequency, resulting in stable transfer of fine droplets with a minimum of large spatter droplets. These characteristics are particularly important when using CO_2 as the shielding gas.

2.3.2 Computer control

As a rapidly controllable power source does not essentially have any characteristics of its own, they have to be produced by electronic or computer control. The most advanced power sources generally incorporate a micro-processor control. The processor can be used for communication, with the user selecting the welding method and making the necessary parameter adjustments. A memory provides a means of saving and reusing previously used settings. Computer control allows maximum utilisation of the flexibility provided by inverter power sources.

- Software control of current output and the welding process.
- Synergy line characteristics, providing optimised settings/performance for each situation.
- Pulsed arc MIG welding.
- Feedback control of welding parameters, guaranteeing improved accuracy and reproduction.
- Improved welding start and stop functions.
- Man/machine communication with the user through the control panel.

The ability to achieve the intended welding quality is improved by the availability and/or use of various functions, examples of which are shown in Table 2.1.

Table 2.1 Examples on functions available on advanced MIG power sources

	Function
Start of welding	Creep start Gas pre-flow Hot start
Continuous welding	Pulsed MIG welding Stepless inductance setting Synergy lines Feedback controlled parameter settings
Finishing a weld	Crater filling Burn-back time setting Shake off pulse Gas post flow

Start of welding

The normal procedure for striking the MIG welding arc is for the gas supply, the wire feed unit and the power unit all to be started when the welder presses the trigger switch on the welding torch. This is also the method that is generally preferred in most cases, as it results in the quickest start.

Sputtering during starting is a problem that can occur from a number of causes. The tendency to sputter increases if the inductance is high and the voltage is low. Welding data that may operate satisfactorily once welding has started is perhaps less suitable when starting to weld.

Creep starting

Creep starting provides a gentler start. The wire is fed forward at reduced wire feed speed until electrical contact is established with the workpiece, after which the wire feed speed increases to the set value.

Gas pre-flow

Gas pre-flow is used when welding sensitive materials, such as aluminium or stainless steel. The gas flow starts a short (and adjustable) time before the arc is struck. The function ensures that there is proper gas protection of the workpiece before welding starts. Note, however, that if the gas hose between the gas bottle and the wire feeder is long, it can act as a ‘store’ for compressed gas, which is then released as an uncontrolled puff of gas when the gas valve opens, involving a risk of creating turbulence around the weld, with reduced protection from the gas. However, a gas-saving valve is available as an accessory, reducing the pressure from the gas bottle and thus eliminating the risk of a puff of gas. The gas pre-flow function will also eliminate this problem because the puff is rather short.

Hot start

The hot start facility increases the wire feed speed and arc voltage for a controllable time during the start of welding. It reduces the risk of poor fusion at the start, before full heat inflow has become established.

Pulsed MIG welding

Pulsed MIG welding is used mainly for welding aluminium and stainless steel, although it is also used for welding ordinary carbon steel. The method, of controlling the molten droplets by pulses (30–300 Hz) from the power unit, makes it possible to extend the spray arc welding range down to low welding data. The welding process is stable and spatter-free, providing a welcome alternative to the use of short-arc welding (see Chapter 6).

Synergy lines

MIG and other welding processes require several welding parameters to be optimised in order to achieve the best results. A popular way of doing this is the use of single-knob control, known as synergic setting of the welding parameters. This represents combinations of parameters that have originally been established by skilled welders, e.g. combinations of wire feed speed, current, voltage, etc., with the results being stored in the memory of the power source. Users start by selecting the required type of process, followed by the type of material, wire diameter and shielding gas. Any subsequent change in the wire feed speed is then compensated by the power source.

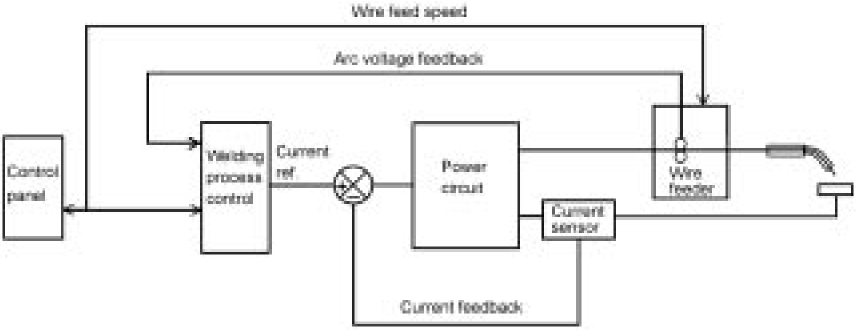
Feedback control

Traditional welding equipment operates without feedback control. Welding voltage varies as the mains voltage fluctuates. The resistance of transformer windings increases when they are heated and also causes a voltage drop that may influence welding quality. More advanced equipment is therefore normally equipped with feedback control that keeps welding parameters to set values and thereby contributes to secure the welding quality (see Fig. 2.9).

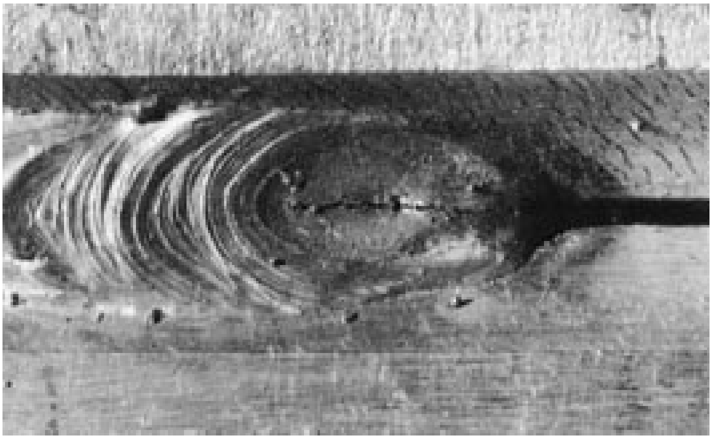
Crater filling

End craters arise as a result of direct interruption in welding. This allows a crack (see Fig. 2.10), or a crater to form when the final part of the metal solidifies, as a result of shrinkage forces during solidification. When grains from opposite sides grow together, low melting-point constituents and impurities can be swept ahead of the solidification front to form a line of weakness in the centre of the weld.

The crater filling function available in advanced power sources can be used to avoid the creation of craters when welds are finished. The arc continues to



2.9 The principle for a process control system with feedback control of welding voltage and current (ESAB).



2.10 A crack may appear as an effect of direct interruption of the welding.

provide a reduced heat input while the weld pool solidifies. This has the effect of modifying the solidification process so that the final part of the weld pool solidifies at the top, thus avoiding the formation of a crater.

Burn-back time

Burn-back time is used in order to ensure that the short length of filler wire that is fed out while the motor in the wire feed unit is stopping is melted off: the welding current can be interrupted more quickly than the wire feed unit can be stopped. If there was no burn-back time, this would have the effect of the filler wire stick-out being too long after finishing the welding. On the other hand, the burn-back time must not be too long, as this would risk melting the entire stick-out and then welding the electrode to the contact tip. When performing mechanised welding, too short a burn-back time can result in the wire solidifying into the weld pool, as the welding torch is not raised on conclusion of welding.

In addition to the time required for the motor to stop, the burn-back time also depends on the type of filler wire, its diameter, the wire feed speed and the particular shielding gas in use.

Shake-off pulse

During the burn-back time, it is easy for a large droplet to form on the end of the wire and then to solidify. This makes starting difficult when the next weld is to be made. By applying a current pulse before the arc is extinguished, this droplet can be nipped off, thus helping the power unit to restart more consistently and more smoothly.

2.4 Rating data for power sources

The power source rating plate (see Fig. 2.11) lists the design ratings of the power source, with the most important being the related values of rated current, rated voltage and duty cycle. Other interesting information shown on the rating plate includes efficiency and power factor, open-circuit voltage, insulation class, etc. EN 60974-1 gives details of how power sources are to be tested and of what information is to be shown on the rating plate.

2.4.1 Standard for welding power sources

The International and European Standard IEC/EN 60974-1 specifies demands on power sources regarding electrical safety. It defines important design principles, rating and testing of the equipment to ensure a safe operation.

ESAB Welding Equipment AB
S-69581 Laxå Sweden
Made in Sweden

AristoArc 400

3~ f1/f2

IEC/EN 60974-1
EN 50199

16 A/21 V - 400 A/36 V

	X	35%	60%	100%
U_0= 78-90V	I_2	400 A	320 A	250 A
	U_2	36 V	33 V	30 V

3~	U_1 400V 50-60Hz	I_{1max} 38 A	I_{1eff} 22 A
	AF	IP 23	S

2.11 Example of a rating plate.

2.4.2 Application class $\boxed{\text{S}}$

This symbol shows that the power unit is designed for use in areas of elevated electrical risk, i.e. in confined spaces where conditions are cramped (with electrically conducting walls or equipment, etc.) or where it is damp.

2.4.3 Enclosure class

The IP code indicates the enclosure class, with the first figure indicating the degree of protection against penetration of solid objects, and the second figure indicating the degree of protection against water. IP 23 is suitable for use indoors and outdoors.

2.4.4 Class of insulation

The transformer and inductor insulation material limits the maximum temperature on the windings. If a power source uses class H insulation material it means that it is made for 180 ºC (20,000 hours). At a heating test of the power source with this class of insulation the rise of temperature in windings is controlled and must not exceed 125 ºC above ambient temperature.

2.4.5 Rated current

The rated current is the current for which the power source is designed. In some cases, a number in the name of the unit may give the impression that it can supply a higher current: always check the technical data or the rating plate to make sure what the actual value of rated current is.

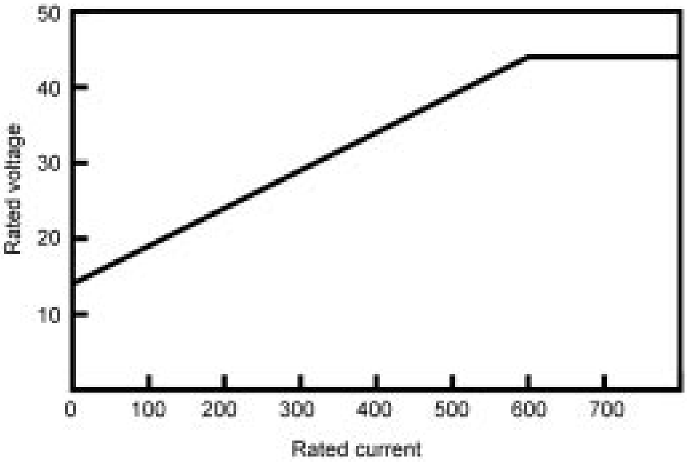
2.4.6 Rated voltage

EN 60974-1 specifies a standard load line which, for each value of rated current, shows the voltage at which the power source must be tested and with which it must be marked (see Fig. 2.12). This means that it is easier to compare the rated data for power sources from different manufacturers. The relationships specified by EN 60974-1 differ from one welding method to another: for MIG welding, the voltages are as follows:

$$U = 14 + 0.05 \cdot I \quad \text{For currents above 600 A:} \quad U = 44\,\text{V}$$

2.4.7 Duty cycle

The power source rating is also determined by its duty cycle, which indicates for what proportion of a period of ten minutes the power source can be operated at the specified load. 400 A at 60% duty factor, for example, means that the power



2.12 The rated voltage for MIG welding power sources.

source can supply 400 A for six minutes in every ten minutes indefinitely without overheating.

2.4.8 Efficiency and power factor

The efficiency indicates what proportion of the input power finds its way through to the welding process. If the efficiency is 75%, this means that 25% of the input power is dissipated in the form of heat losses in the power source.

$$\text{Input power} = \frac{\text{Welding current} \cdot \text{Welding voltage}}{\text{Efficiency}}$$

The actual power demand can then be calculated if the efficiency is known. The active power supplied to the source is measured in kW, and determines the energy cost.

The current to be supplied by the mains, and thus passing through the supply fuses, increases if the efficiency is poor. However, in order to be able to work out the supply current, we also need to know the power factor. For a 3-phase supply, we have:

$$I_1 = \frac{P_1}{U_1 \cdot \sqrt{3} \cdot \lambda}$$

where: I_1 = mains current [A]
P_1 = input power [W]
U_1 = supply voltage [V]
λ = the power factor

The power factor depends partly on the phase displacement between the current and the voltage, and partly on the shape of the current waveform, if this departs from a sine wave. Multiplying the current and voltage gives the apparent power, which is measured in kVA and which is of importance when determining the capacity of the electrical supply system. The power factor is defined as the ratio of true power to the apparent power.

Typical values of power source efficiency are in the range 0.75–0.85. The power factor can be as high as 0.95, e.g. for a MIG power source with tap-changer control or for certain inverter units, although it is usually considerably lower for MMA power sources.

2.5 Electrical safety requirements

It is important from the point of view of electrical safety that the open-circuit voltage of the power unit is not too high. IEC/EN 60974-1 permits a maximum peak voltage of 113 V if direct current is used.

A welding circuit is not protectively earthed: therefore it is particularly important that the power source is well insulated in order to ensure that the mains voltage cannot reach the secondary circuits.

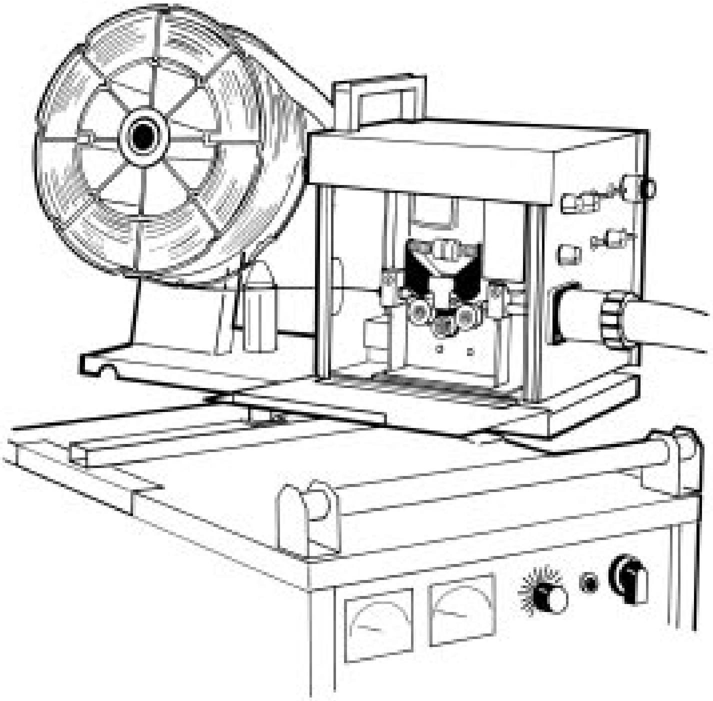
Transformer winding insulation is exposed to high temperatures, so the material must be of a suitable insulation class to withstand the temperature. A rise of 10 °C reduces the life of the material by half. Therefore it is particularly important to keep the interior of the power source clean in order to maintain adequate cooling performance.

Power sources used outdoors should be designed so that moisture and rain cannot degrade the insulation performance and cause short circuiting with possible dangerous consequences.

2.6 Wire feed unit

The wire feeder system is a critical part of the equipment. The wire has to be pushed through the flexible conduit that can be up to five metres long. Start and stop of the wire feed must be very fast and the speed of the wire must be smooth and not vary, as that would directly influence the welding quality.

The wire reel is placed on a brake hub with adjustable friction (see Fig. 2.13). The intention is to stop rotation when the feeding is stopped in order to keep the wire in place. The electrode is passed to the drive rolls, which then push the wire through the hose package. Even in normal use it is common that the friction varies, e.g. when the curvature of the hose is changed or when particles or dirt fill up the wire conduit. The wire speed must not vary too much, otherwise this could result in unwanted variations in the welding data. Superior control of the wire feed speed can be achieved if the motor is equipped with a pulse generator and feedback system. The wire conduit is normally spiral metal but for aluminium a low friction plastic (Teflon) type is recommended.



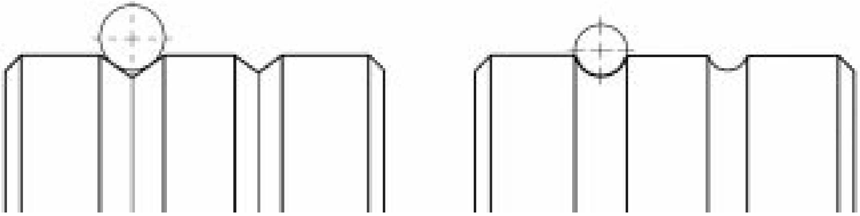
2.13 A wire feed unit with wire reel.

In order to transfer feeding force into the wire the rollers must be pressed against each other. The force must be enough to maintain a steady feed but must not deform the wire too much. In order to increase the contact surface the drive rolls have a trace that fits to the wire (see Fig. 2.14). Also the number of driven rolls and their diameter influences the feeding force that can be achieved. There are some different alternatives available.

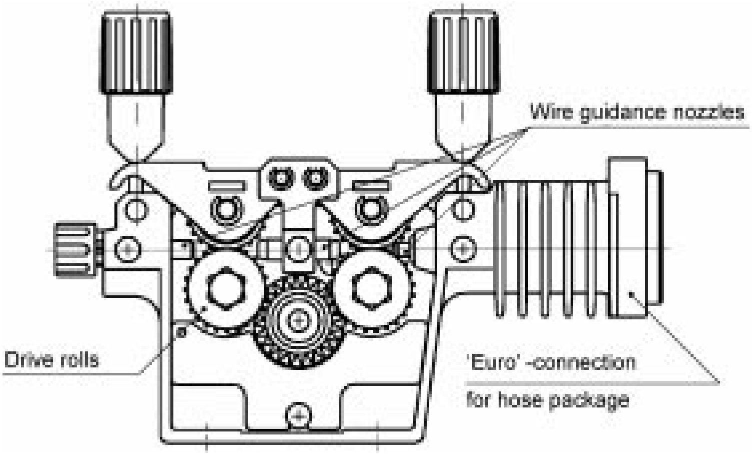
- Two feed rollers where one is driven and the other is a spring loaded pressure roller. Often just the driven roller is grooved and the other flat.
- Two drive rollers.
- Four drive rollers (see Fig. 2.15).

2.6.1 Push–pull feeding principles

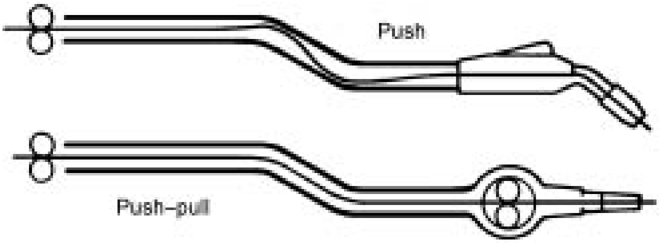
The wire feed system with pushing rolls in the wire feeder is a standard solution that is sufficient in most cases, but for softer wires such as aluminium other solutions are recommended. For instance, a push–pull system with feeding devices both in the wire feeder and in the gun (see Fig. 2.16). This system reduces the friction that otherwise will be built up in every curve of the conduit and gives very stable feeding properties. It allows also a gun hose length of up to



2.14 Drive rolls with different types of traces are used. For soft electrode material such as aluminium or flux cored wires, U-type traces are recommended.



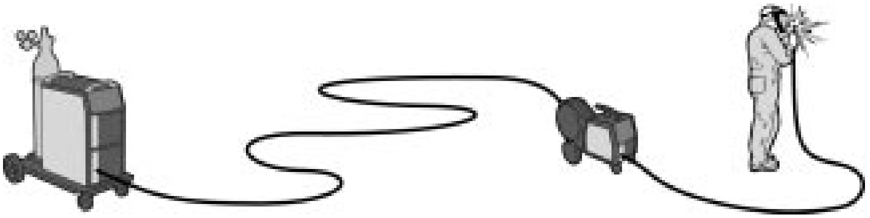
2.15 Heavy duty four-wheel drive assembly (ESAB).



2.16 The difference between a push and push–pull wire feed system. In only a push or pull wire system friction is built up and increased in every curve of the conduit. This is avoided by the use of a push–pull system.

15 m and is therefore used to increase the operating range for the welder. The best system is maybe when a dominating gun motor is used. The rear push motor then works as a slave to the gun motor. The push motor has a limited torque.

When just reach is of importance, a normal gun can be used together with an intermediate wire feeder. The intermediate feeder is connected with the ordinary wire feeder by a 25 m long hose package (see Fig. 2.17).



2.17 An intermediate wire feeder is useful at yards or other places where long reaching is essential (ESAB).

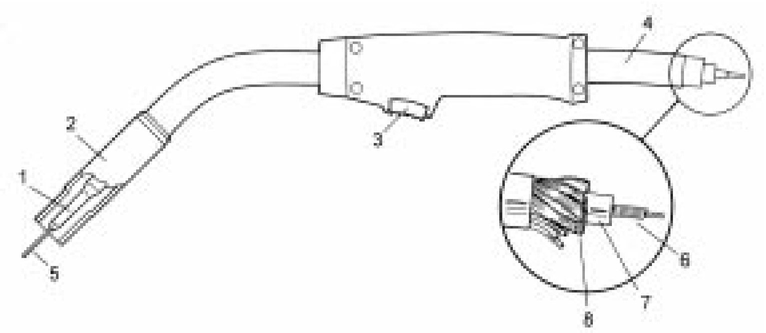
Another solution to the feeding problems is a welding gun equipped with its own small wire reel. The size and weight of the gun increases and the wire tends to be more expensive on the small reels. At least in Europe, therefore, the push–pull system has become most popular.

2.7 Welding gun and feeding properties

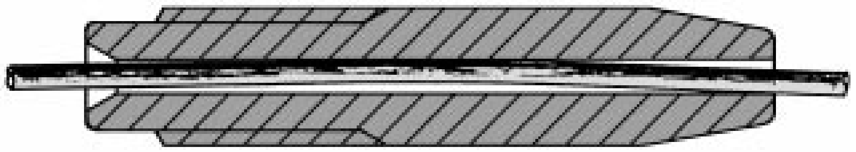
The welding gun with hose package (see Fig. 2.18) is an important part of the welding equipment. It brings the shielding gas, electrode and welding current to the arc. It is difficult to design a robust welding gun for the tough environment and at the same time make it small and light enough to be acceptable for working in narrow spaces. Welding guns for higher currents are often water cooled. If the current cable, contact tip and gas nozzle are cooled the size and weight of the gun can be reduced.

2.7.1 Contact tips

The contact tip is the most critical part in the welding gun. It is important that the current is transferred to the wire close to the front end. When the contact tip



2.18 Welding gun with hose package. 1. Contact tube. 2. Shielding gas nozzle. 3. Trigger switch. 4. Hose package. 5. Electrode. 6. Flexible conduit. 7. Shielding gas hose. 8. Power cable (ESAB).



2.19 Good electrical contact is achieved thanks to the cast of the wire (ESAB).

is worn the position of the contact point may vary and that causes a less stable welding process.

As shown in Fig. 2.19, the electrical contact is dependent on the angle between the wire and the contact tip. Normally the curvature of the wire is enough to get this contact.

The contact tip is heated from the welding arc, the pool and from the resistive heating of welding current. It can reach temperatures above 300 °C and that influences both the hardness and the electrical conductivity of the tip. Special alloys such as CuCrZr are recommended, rather than pure copper, and show much higher hardness and durability at high temperatures. Experience shows that careful maintenance is necessary to avoid disturbances when the contact tip is exposed to hot and heavy operation.

A clearance between wire and contact tip bore size is important. For short-arc welding 0.2 mm is employed and for spray arc 0.3–0.5 mm.

Spatter has a tendency to fasten to rough surfaces and sharp edges, therefore contact tips with a smooth finish and rounded edges would be preferred.

2.7.2 Burn-back

Burn-back occurs when the arc for some reason melts the wire up to the contact tip. The wire is then welded or fixed to the tip and then crumpled up at the feeding rollers. The reason can be a bad start or that the contact tip or wire conduit is clogged with dirt or metal debris. High current surges at start-up may create a micro-weld to the wire inside the contact tip. Depending on the length of wire conduit and clearance in it, the feeding force is not immediately built up and therefore not able to release the wire before the burn-back has occurred. Argon rich gases increase the risk of burn-back as they allow a long arc.

2.7.3 Preventive maintenance

- At higher welding data the heat from the arc increases. It is important to choose the proper size of gun to avoid temperature overload.
- Use a water-cooled gun when necessary.
- Keep the gun free from spatter. Spatter will catch more easily to a hot surface. Anti-spatter fluid, which is regularly sprayed on the surfaces exposed to spatter, is recommended to facilitate cleaning of the front parts of the gun.

- Choose a proper wire stick-out. Too short a distance will increase the risk for burn-back of the arc. That will also increase the heat take-up from the arc.
- Carefully choose the clearance between wire and the inner diameter of conduit. A small clearance increases the risk of stoppage and too large a clearance will give irregular feeding.
- Follow recommendations from the manufacturer carefully on how to cut the exact length of the conduit.
- Adjust the brake in the wire reel hub to avoid excessive braking of the wire.
- When welding with aluminum wires, special care must be taken to avoid feeding problems. The wire guidance nozzles, see Fig. 2.14, close to the feeder rollers and the wire conduit need to be of the low friction plastic type. Rounded, U-shaped roller traces are recommended for aluminium. Avoid excessive pressure on the drive rollers.
- When feeding problems occur, the reason could be that metal particles from the wire have increased the friction in the conduit. Just to stretch the pressure between the feeder rolls is not always the best action. That may result in increased deformation of the wire and just produce more particles. To avoid further problems it is recommended to blow the conduit clean now and then.
- Use a dust cover for the wire reel wherever it is exposed to plant environment.
- For the most critical usage, such as an extra long hose package or the use of soft aluminium wires, a push–pull wire feeder (see Fig. 2.16) is recommended.

2.8 Cooling units

Water-cooled welding torches are often used in the higher current range (300–500 A). Cooling water is circulated from a cooling unit, which may be separate or be incorporated in the power source. The water cools the copper conductor in the hose, the gas nozzle and the contact tip. Cooling units normally include a water container, a pump and a fan-cooled radiator. It can be built in to the power source or be separate from it.

2.9 Bibliography

ESAB and AGA (undated) *Facts about MIG/MAG welding*. ESAB Welding Equipment AB.

Houldcroft, P and John, R (1988) *Welding and cutting*, Cambridge, Woodhead-Faulkner.

Villafuerte, J. M. Asc. (2004) *Caring for your contact tips. http://www2.thefabricator.com/Articles/Fabricating_Article.cfm?id=968*

Weman, K (2003) *Welding processes handbook*, Cambridge, Woodhead.

3

Shielding gases in MIG welding

G LINDÉN, Air Liquide Gas AB, Sweden

3.1 Introduction

The shielding gas eliminates the influence of the surrounding air on the welding process and affects the welding process. The selection of the type of gas depends on the properties required.

The shielding gas must also be available at a reasonable price. The different gases used are separated from the air (argon, oxygen, nitrogen), are available from the chemical industry (hydrogen, carbon dioxide) or are possible to extract from certain natural gas sources (helium). Either pure gases or mixtures of gases are used in MIG welding. Minor amounts of more rare gases are added for certain purposes. The gases must be in a gaseous state but can be delivered to the user either in high-pressure gas cylinders or in a liquid state that is vapourised and sometimes mixed in a gas mixer before use.

It is necessary to have a high purity gas and a tolerance of the mixing ratio of the gas mixture. There are requirements in both American and European standards that will be discussed below.

At the end of this chapter, the gas supply and gas safety aspects will also be discussed.

3.2 The role of the shielding gas

The shielding gas has two main functions:

- To protect the process and material from the surrounding air and in specific cases give a shielding atmosphere that reduces oxides on the heated material near to the weld.
- To affect the process regarding arc stability, productivity, reliability, quality and work environment.

In order to achieve a weld with acceptable quality the influence of the surrounding air must be minimised. The air influences the melted material in the weld pool that may dissolve oxygen and nitrogen. The oxygen and nitrogen appear both in solid solution and as oxide and nitride particles that may give harmful effects on the material properties after solidification. The air also influences the surface of the melted and hot solid metal mainly by oxidation or pore formation. The shielding gas protects from the influence of the air. In MIG welding with solid electrodes the deoxidation is partly dependent on the electrode composition and partly on the shielding gas. The electrode contains elements, e.g. silicon to react with oxygen and form oxides in the slag that normally appears as small islands on the surface. If flux-cored electrodes are used there are also special slag-forming elements in the flux. There will be a combination of these effects that gives the quality of the final weld.

Another important effect of the shielding gas is to improve the process. Some of these factors are:

- Ignition of the arc.
- Arc stability.
- Material deposition.
- Wetting between solid material and the weld pool.
- Penetration depth and shape.
- Spatter formation.
- Emission of airborne pollutions.

The properties of the pure gases and the different gas mixtures are governed by the physical and chemical characteristics at low as well as at high temperatures. The temperature is up to more than 8000 K in the centre of the arc and depends on shielding gas, welding parameters, etc. The electrical conduction in the arc plasma and the heat conduction depend on the gases used. In the plasma the gases with two or more atoms in the molecule are dissociated into atoms. The atoms are then ionised at still higher temperatures. The energy needed to form the plasma with atoms and ions is regained at the arc root and melts the material and filler material.

3.3 Standardisation of the shielding gases

In the European standard EN 439 *Welding consumables – Shielding gases for arc welding and cutting* the shielding gases for different methods are classified according to their chemical properties. The gas purities and mixing tolerances of gas mixtures with two or more gases are also specified. In the following subsection EN 439 will be discussed in detail.

A similar specification is found in AWS Specification 5.32 *Specification for welding shielding gases*.

3.3.1 Classification

The gases included in the EN 439 are argon, helium, carbon dioxide, oxygen, nitrogen and hydrogen. The physical and chemical properties are summarised in

Table 3.1 Properties of gases used in MIG welding (EN 439)

Type of gas	Chemical symbol	Specified at 0 °C and 1.013 bar (0.101 MPa)		Boiling point at 1.013 bar	Reaction behaviour during welding
		Density (air = 1.293) kg/m^3	Relative density to air		
Argon	Ar	1.784	1.380	−185.9	Inert
Helium	He	0.178	0.138	−268.9	Inert
Carbon dioxide	CO_2	1.977	1.529	−78.5*	Oxidising
Oxygen	O_2	1.429	1.105	−183.0	Oxidising
Nitrogen	N_2	1.251	0.968	−195.8	Unreactive
Hydrogen	H_2	0.090	0.070	−252.8	Reducing

* Sublimation temperature (solid to gas transition temperature).

Table 3.1. Only helium and hydrogen are considerably lighter than air. Carbon dioxide and argon are much heavier than air. At room temperature all are gaseous. In compressed state normally (200 to 300 bar in cylinders) all of them are still gaseous except carbon dioxide, which is liquid above about 50 bar at 15 °C.

Argon and helium are inert, which means that they do not react with the metals. Oxygen and carbon dioxide are both oxidising. Carbon dioxide dissociates in the welding arc forming oxygen atoms. Thus, it also has an oxidising effect. It is lower than that of oxygen; often considered as half of that of oxygen. The nitrogen-containing mixtures in the EN-standard are used for root shielding mainly in TIG welding. Anyway, minor additions of nitrogen are used in MIG welding for certain stainless steels (see below). Nitrogen is characterised as non-reactive but at the high temperatures in the arc it is also dissociated and reacts with the weld pool and the hot material. Hydrogen is a reducing gas at higher temperatures. This means that oxides can be dissolved or prevented from being formed but its use is limited to certain materials.

To combine the effects of different gases they are often used in gas mixtures. In the EN-standard the classification is based on their chemical reactions. The different groups are:

- R: reducing gas mixtures.
- I: inert gases and inert gas mixtures.
- M: oxidising mixtures containing inert gases together with oxygen, carbon dioxide or both.
- C: highly oxidising gases and gas mixtures.
- F: unreactive gas or reducing gas mixtures (used for plasma welding and root shielding).

Table 3.2 shows the classification for gases used in MIG welding.

Table 3.2 Classification of shielding gases for are MIG welding (EN 439)

Symbol		Components in percent volume						Typical applications	Remarks
Group	Identification no.	Oxidising CO_2	O_2	Inert Ar	He	Reducing H_2	Unreactive N_2		
R	1			Balance*		>0 to 15		TIG plasma arc welding, plasma arc cutting, back shielding	
	2			Balance*		>15 to 35			
I	1			100				MIG, TIG, plasma arc welding, back shielding	
	2				100				
	3			Balance	> to 95				
M1	1	>0 to 5		Balance*		>0 to 5		MAG welding	Slightly oxidising
	2	>0 to 5		Balance*					
	3		>0 to 3	Balance*					
	4	>0 to 5	>0 to 3	Balance*					
M2	1	>5 to 25		Balance*				MAG welding	
	2		>3 to 10	Balance*					
	3	>0 to 5	>3 to 10	Balance*					
	4	>5 to 25	>0 to 8	Balance*					
M3	1	>25 to 50		Balance*				MAG welding	
	2		>10 to 15	Balance*					
	3	>5 to 50	>8 to 15	Balance*					
C	1	100						MAG welding	More pronounced oxidation
	2	Balance	>0 to 30						

Balance* Argon may be replaced by up to 95% helium.

Table 3.3 Identification numbers for gases in groups R and M containing helium (EN 439)

Identification number	Helium content in volume %
(1)	> 0 to 33
(2)	> 33 to 66
(3)	> 66 to 95

The group R 1 contains gases with additions of hydrogen in argon. They are mainly used in TIG welding. The group I contains three classes I 1 with 100% argon, I 2 with 100% helium and I 3 with mixtures of argon and helium. The group M is divided in subgroups in two levels with different amounts of CO_2 and O_2. The different oxidising effect of the two gases is also taken into account. Slight oxidation in the lower numbers up to M 11 (also containing minor addition of hydrogen) and high oxidation in higher numbers up to M 33. In both R and M groups the argon can be substituted by helium in the mixtures and this is denoted by a number in parenthesis (Table 3.3). The most important subgroup in the group C is C 1 containing 100% CO_2.

An example of the designation for an argon-rich gas with 25% He and 2% CO_2 is Shielding gas EN 439 M12(1).

Gas mixtures not included in the classification system are denoted by an S, followed by the gas or mixture symbol, followed by the percentage by volume and chemical formula of the additional gases. An example is an Ar/N_2 mixture with 2% of N_2 which is designated S I1 + 2% N_2.

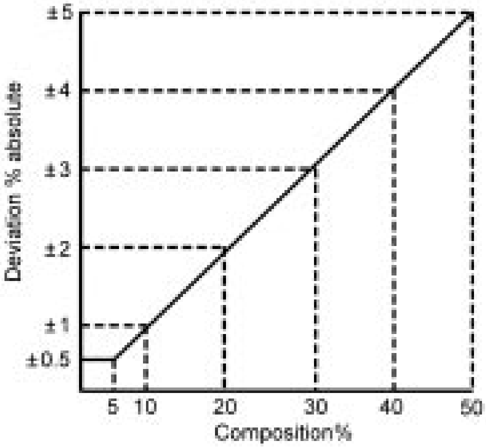
3.3.2 Tolerances of mixtures

The tolerances of the mixtures are also specified in the standard. For components up to ±5% the permissible deviation shall not exceed 0.5% from the specified value. Higher component concentrations up to 50% may not deviate more than ±10% of the component concentration. For a mixture of 20% of carbon dioxide in argon the mixture must have a composition of $20 \pm 2\%$ CO_2 (see Fig. 3.1).

On some occasions with increased demands on quality it is necessary to have more strict requirements than those indicated by the standard.

3.3.3 Purities and dew point

A prerequisite to get the right mechanical properties of the weld and no porosity is to have high purity of the gases and low amount of moisture. The requirements from the standard are shown in Table 3.4.



3.1 Allowed deviations from the specified value in shielding gas mixtures according to EN 439.

The global purity is given for the different groups. The demands on the inert gases are highest, somewhat lower on the oxidising mixtures and CO_2. For the moisture there are two alternative ways of presenting the content either by the dew point or by the volume of water in parts per million (ppm).

Even if the requirements on the gases in cylinders, or from liquid state, are rigorous the purity must be assured up to the point of use. This includes:

- Tight and dry hoses and tubes.
- No leakage in connections.
- No leakage of water or air into the welding guns.
- Gas flow without disturbance.
- Correct gas flow rate.
- Right angle of the welding gun to avoid ejection of air into the shielding area.

Table 3.4 Purities and dew points of gases and gas mixtures (EN 439)

Group	Purity % by vol min.	Dew point at 1.013 bar °C max.	Moisture ppm max.
R	99.95	−50	40
I	99.99	−50	40
M1	99.70	−50	40
M2	99.70	−44	80
M3	99.70	−40	120
C	99.70	−35	200

3.4 The properties of the individual gases

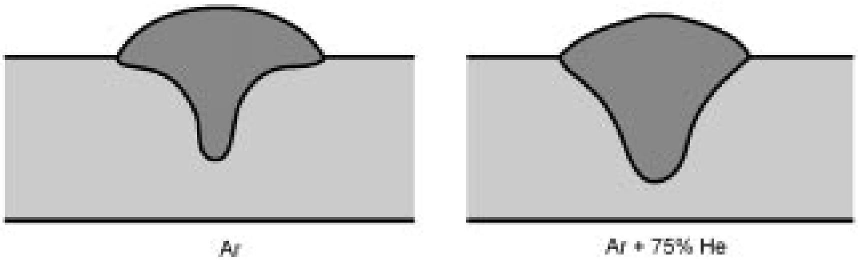
The EN standard mainly concentrates on the properties of the gases from a chemical point of view. This regards their influence on the formation of oxides in the weld metal and on the surface of the material. There are other properties connected to the welding that influence surface appearance, porosity, productivity, etc. In this section the properties of the pure gases and the properties that are influenced with additions of the different gases are discussed.

3.4.1 Argon (Ar)

Argon is an inert gas, which means that it does not react chemically with any material under normal conditions. It is produced in an air separation plant, where the gases oxygen, nitrogen and argon are liquefied and separated by a diffusion process. A very high purity is possible to reach. It can easily be transported either in liquid state or in cylinders after vapourisation and filling.

Argon is possible to use together with all metals. It is used either alone or together with other gases in mixtures. Most shielding gases have argon as the main component.

In the welding arc argon is easily ionised, which is a basis for a good arc initiation. The heat conductivity is relatively low. This also means that the arc voltage is fairly low, lower than for electric arcs with helium or different gas mixtures. The heat input will be fairly low. The penetration in spray arc is finger-like. This is also the case when mixtures with high argon content are used. Low heat input in combination with the finger-like penetration may give a risk of porosity and lack of fusion depending on limited sidewall penetration (see Fig. 3.2). To get a stable arc in welding of steel, oxidising additions in the gas mixture must be used. Normally oxygen or carbon dioxide is used.



3.2 The influence of shielding gas on penetration in MIG welding of aluminium at high currents. Argon gives a finger-like penetration. Additions of helium give wider and deeper penetration.

3.4.2 Helium (He)

Helium, like argon, is an inert gas. The amount of helium in air is small, 0.0005%, so the commercial production of helium is based on certain natural gas sources with a high helium content of more than 0.4%. After extraction from the natural gas the helium is purified. It can be transported either in liquid state or in cylinders. The boiling point is 4 K, which is near to absolute zero. This needs special care for the insulation of the container used for liquid helium. The shortage and more difficult production of helium make it more expensive than other gases. This also means that helium and helium additions are mainly used where special advantages are required.

Helium can be used with all metals. It is normally used in mixtures and seldom as a single gas. In contrast to argon, helium is difficult to ionise and the arc initiation is bad. The heat conductivity is much higher compared to argon. The arc voltage is much higher than for argon. The heat input is therefore much higher at the same arc current. The arc is less concentrated which gives a wider and deeper penetration (see Fig. 3.2). Hot cracking and porosity are more easily avoided. The wetting of the surface is better. This gives a lower reinforcement and less risk of undercut.

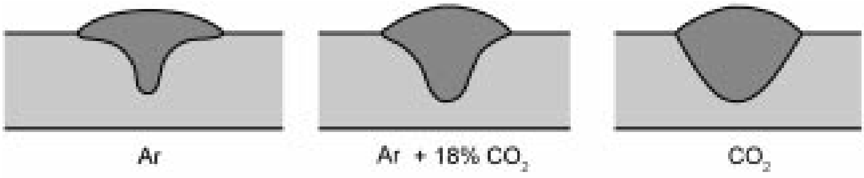
Helium has a low density and mixtures with high amounts of helium have a worse shielding effect compared to argon. A higher gas flow rate must be used.

3.4.3 Carbon dioxide (CO_2)

Carbon dioxide is used either alone or as a component in argon-based mixtures. It is available from chemical industries where it is a by-product in certain chemical processes. After purification to acceptable quality it can be used in MAG welding. It is a relatively cheap shielding gas since it is easily available.

CO_2 does not react with metals at room temperature but is an active gas in the arc. The molecule dissociates at about 1500 °C forming free oxygen atoms. They can react with the material, filler material and weld pool. Alloying elements, mainly manganese and silicon, react forming slag in the weld or on the surface. This decreases the amount of alloying elements in the melted material but is compensated for by a higher alloyed filler material. The alloy content of the weld material is important for the mechanical properties.

Owing to the dissociation of the molecules the necessary voltage increases. The heat conductivity is also higher in the arc. This leads to a higher energy transfer to the weld pool and a wider penetration without the finger-like penetration found with argon as a shielding gas (see Fig. 3.3).



3.3 The influence of additions of carbon dioxide to argon on bead profile and penetration. MAG welding of plain steel.

3.4.4 Oxygen (O_2)

Oxygen is used only as a minor component in the gas mixture. The maximum amount is about 10%. It is produced in an air separation plant in the same way as argon. There is about 21% of oxygen in the air. From the air separation plant the oxygen is delivered in liquid state. After vapourisation it is mixed with argon, sometimes together with CO_2. Another way to produce very pure oxygen is from electrolysis of water. This is often combined with the production of hydrogen.

Oxygen forms oxide on metals especially at high temperatures and this is not wanted in welding. However, some oxidising elements are needed to stabilise the welding arc in MAG welding. In this case oxygen is an alternative to CO_2. In the same way as CO_2, the forming of slag together with certain alloying elements in steel decreases the mechanical properties.

The surface energy decreases in the liquid droplets in the arc and in the weld pool. This gives a more fluid weld pool, good appearance of the weld surface but more difficult positional welding.

3.4.5 Nitrogen (N_2)

Nitrogen is used as a component in certain shielding gas mixtures for austenitic and duplex stainless steels. The maximum amount is about 5%. 100% nitrogen can be used as a shielding gas for the welding of copper. Nitrogen is produced in air separation plants and delivered in liquid state.

At room temperature nitrogen is an inert gas. At high temperatures in the welding arc nitrogen is dissociated and reacts with the weld pool and dissolves in the melted material. In unalloyed steels there can be formation of nitrides that may be detrimental to the mechanical properties. Nitrogen is therefore unsuitable as a component in the shielding gas in this case. Since nitrogen is an alloying element used in ferritic–austenitic duplex steels small additions in the shielding gas can compensate for the nitrogen that is lost from the weld pool during welding. In the same way nitrogen can be used as an austenite-forming element in austenitic stainless steels if fully austenitic material is required. Too much nitrogen in the shielding gas leads to porosity.

Another application of nitrogen is used mainly in TIG welding for root protection in stainless steel to avoid formation of oxides. Either nitrogen of high purity or mixtures of nitrogen and hydrogen are used.

3.4.6 Hydrogen (H_2)

Hydrogen is used as a minor component in gas mixtures for austenitic metallic materials mainly austenitic stainless steels, nickel and nickel alloys. Hydrogen is most often produced by electrolysis of water, and is afterwards compressed in gas cylinders. Hydrogen is a flammable gas but the mixtures used in MIG welding hold only up to 5% of hydrogen. The flammability limit of the mixture of argon and hydrogen is 2.8% according to ISO 10156.

The austenitic microstructure is not adversely affected by the presence of small additions of hydrogen. Higher amounts of hydrogen lead to porosity. The voltage required to create the arc is increased, which gives increased heat input. This depends on the dissociation of the hydrogen molecule at fairly low temperatures in the arc. The welding speed can be increased. Often, argon is used in combination with helium and hydrogen. A small amount of CO_2 is used for arc stabilisation. Hydrogen also acts chemically to reduce the oxides and gives a very clean surface. Owing to the risk of porosity hydrogen-containing mixtures are normally recommended for welds with one bead only.

3.4.7 Other elements

Small amounts of other gases are sometimes considered to improve the directional stability of the arc. Besides the already mentioned oxidising gases CO_2 and O_2, N_2 and NO are also used for this purpose especially for aluminium welding. The amounts are of the order of 0.1% or lower.

3.5 The gas mixtures for different materials

The gases described above can be used either as individual gases or in combination in order to achieve properties suitable for each situation. The properties of the individual gases are combined in the mixtures but each individual mixture emphasises certain advantages. There are also limitations to take into account.

One important point is the influence of the mixtures for the drop transfer modes. MIG welding is characterised by material transfer from the heated electrode to the weld pool. This has been discussed in Section 1.2. The welding parameters (current, voltage, stick-out, etc.) in combination with the shielding gas used give different results.

3.5.1 Unalloyed and low-alloyed steel and solid wires

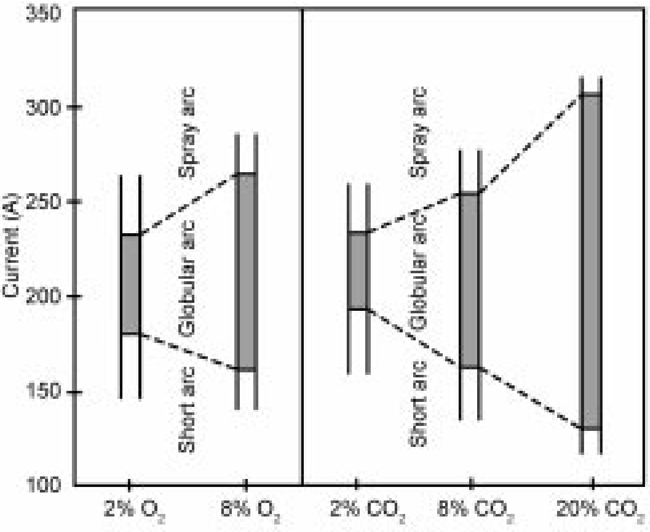
In short-arc welding the heat input is low owing to the low voltage and current. The drop transfer is characterised by short-circuiting between the wire and the weld pool. This method is suitable for thin steel sheet. There is a good bridging capacity with this transfer mode.

Mixtures of Ar with CO_2 and/or O_2 are used. Low amounts of oxidising gases are favourable to get low spatter. Ar with CO_2 up to 25% is used. The more CO_2 the better the possibility will be in positional welding. The process parameters are easier to control with the argon mixture compared to pure CO_2. Lower amounts of CO_2 and O_2 in the shielding gas give less oxide of silicon and manganese on the bead and less cleaning is necessary.

Pure CO_2 is not preferred for welding with higher currents and voltages. The drop transfer will be irregular and a lot of spatter is emitted from the solid wire. A spray arc mode is not achieved for pure CO_2. To achieve spray arc welding with Ar/CO_2 mixtures, a maximum of about 25% CO_2 is acceptable. The higher the CO_2 content, the wider the weld will be and this gives a safe penetration and

Table 3.5 Comparison between different shielding gases for welding of unalloyed steel

Property	Ar + 8% CO_2	Ar + 20% CO_2	100% CO_2
Penetration	Narrow and shallow	Intermediate	Wide and deep
Arc transfer	Short arc, spray arc, pulsed arc	Short arc, spray arc, pulsed arc	Short arc mainly
Easy to find parameters	Good	Good	More difficult
Porosity	Good	Better	Best
Risk of lack of fusion (higher thickness)	Highest	Less	Least
Spatter	Least	More	Most
Oxides on the bead	Least	More	Most
Positional welding	Less good	Good	Good
Thin sheet welding	Best	Good	Good
Zinc-coated steel	Less good	Good	Best
Rusty surface	Less good	Good	Best
Heat in the welding gun	Good	Good	Best cooling from CO_2
Draught sensitivity	Good	Good	Best



3.4 The influence of the argon mixtures with different oxygen and carbon dioxide additions on the globular region (Air Liquide).

low porosity. The risk of lack of fusion is lower with more CO_2, see Fig. 3.3. A comparison between the properties with CO_2 and two argon–CO_2 mixtures as shielding gases is made in Table 3.5.

Oxygen additions favour the fluidity of the weld pool. This is advantageous for the surface smoothness but makes positional welding more difficult. The arc stability is good with additions of O_2. At higher currents the finger-like penetration from argon is evident. The sidewall penetration is decreased compared to CO_2. A combination between O_2 and CO_2 in argon gives a fruitful compromise.

Globular transfer appears at arc currents and voltages between the short-arc and spray-arc regions. Globular transfer is irregular and the spatter is high. For the welder it is often necessary to increase productivity by using parameters near to the limit of the short-arc region. Low amounts of CO_2 and O_2 in the argon mixture favour a small globular region and a large short-arc region (see Fig. 3.4).

In order to avoid the globular transfer region pulsed arc welding can be used. It is more difficult using argon mixtures with a high amount of CO_2. The best result is achieved with as low as 8% or even lower. Oxygen additions or mixtures of CO_2 and O_2 can also be used.

3.5.2 Unalloyed and low-alloyed steel welded with flux-cored wires

The composition of the flux in the flux-cored wires is normally balanced to adapt to a specific shielding gas mixture. In these cases it is very important to keep to the specifications given by the manufacturer of the wire. Pure CO_2 is sometimes used but is often prone to spatter formation. An Ar/CO_2 mixture with 18–20% CO_2 is very often prescribed. The mechanical properties as well as the penetration, the weld bead shape and the arc stability will be better.

3.5.3 Stainless steel

The most common stainless steels have an austenitic microstructure. Welding with only argon or argon–helium gives an unstable arc, finger-like penetration and bad wetting between the weld and the base material. Small additions of CO_2 (1–3%) or O_2 (1–3%) improve this situation. On the other hand, the oxidation of the surface will increase. CO_2 addition is better since the oxidation is lower. For austenitic steels with very low carbon content there is a risk of carbon increase in the weld. With an addition of up to 3% CO_2 this is not a problem. The carbon pick-up is related to the use of the extra-low carbon containing austenitic stainless steels in environments with a risk of intergranular corrosion cracking.

In order to increase the welding speed helium partly replaces argon. Helium also gives a wider penetration. Small additions of hydrogen (1–2%) are also possible. The energy in the arc increases, the penetration will be wider and the slag on the surface decreases. Hydrogen improves the surface finish since it reduces the oxides or prevents the formation of oxides. Hydrogen-containing gases are normally used only for welding in one pass. In welding with more than one pass there is a risk of build-up of hydrogen leading to porosity.

Shielding gas mixtures of the same type except those containing hydrogen can also be used for duplex (ferritic–austenitic) stainless steels and for ferritic steels. The duplex steels are normally alloyed with nitrogen. In the high temperatures at the weld pool some of the nitrogen in the steel has a tendency to disappear. This can be compensated by the introduction of a small amount of nitrogen in the shielding gas. A typical addition is 2%. Too much nitrogen can give porosity.

Most flux-cored electrodes for stainless steels are developed for argon–CO_2 mixtures with 18–20% CO_2. Pure CO_2 can also be used. The alloy content and the deoxidation elements in the flux and filler material assure that the weld metal will get the right properties.

3.5.4 Aluminium and aluminium alloys

Aluminium and aluminium alloys have a tenacious oxide. The oxide also binds water and it is recommended that the oxide is removed before welding. There is also a tendency that the oxide will sink in the melted material during welding and be included as inclusions in the weld metal.

The most commonly used shielding gas is argon which gives sufficient stability to the welding arc. Minor additions of other gases may, on different occasions, improve the stability of the arc. Aluminium metal has a high thermal conductivity and therefore it is advantageous to increase the heat transfer of the shielding gas. Helium additions are then used. Up to 80% helium in argon improves the penetration but does not affect the arc initiation negatively. 100% helium is not suitable from the arc initiation point of view. Helium widens the arc and improves the bead shape. The welding speed is increased. Porosity will also be lower.

Argon with 1–2% of oxygen can be used to increase the bead penetration and the welding speed but the surface becomes oxidised and there will also be oxide inclusions in the weld metal.

It is not possible to use hydrogen in gas mixtures for aluminium welding in spite of the austenitic microstructure of the material. The reason is that the dissociated atoms of hydrogen have a very high solubility in the weld pool but a very low solubility in the solid metal. Since there are difficulties for the high amount of hydrogen to escape during solidification, there will be extensive porosity caused by the hydrogen molecules. The same problem comes from moisture chemically bonded in the aluminium oxide on the surface of the material. The water dissociates into hydrogen and oxygen and the hydrogen atoms dissolve in the weld pool.

3.5.5 Titanium

Titanium is welded with high purity argon. Titanium metal is sensitive to both nitrogen and oxygen in the shielding gas. The surface must be cleaned carefully to remove the oxide before welding. Oxygen in the weld metal is detrimental to the mechanical properties. Helium additions can also be used to increase the heat input. Titanium is more often welded with the TIG process.

3.5.6 Copper and copper alloys

For welding of copper and copper alloys argon is normally used. The high thermal conductivity of copper may need preheating of the material. Thicker material that needs more heat is preferably welded with a mixture of argon and helium. These mixtures give good penetration and bead shapes. The need for preheating is also reduced. Helium alone may also be used.

Argon with 20–30% nitrogen can be used since nitrogen has no negative metallurgical effect on copper. The nitrogen increases the heat input and gives a deep penetration.

3.5.7 Nickel and nickel alloys

Nickel and nickel alloys are normally welded with argon or argon/helium mixtures. The addition of helium leads to wider and flatter beads. The use of additions of O_2 or CO_2 in the same way as for steel is not good. Even small

Table 3.6 Generally recommended shielding gases for MIG welding (for details see text)

Material	I1 Ar	I3 Ar/He	M11 $Ar/He/CO_2/H_2$	M12 $Ar/He/CO_2$	M13 $Ar/He/O_2$	M14 $Ar/CO_2/O_2$	M2 $Ar/CO_2/O_2$	C1 CO_2
Unalloyed and low-alloyed steels						●	●	●
Austenitic stainless steels	❍	❍	●	●	●			
Other stainless steels	❍	❍		●	●			
Aluminium and alloys	●	●						
Copper and alloys	●	●	❍					
Nickel and alloys	●	●						
Titanium	●	●						

● normally used
❍ sometimes also used

amounts will result in oxidised bead faces and irregular beads. Small amounts of CO_2 are advantageous in stabilising the arc. Since nickel has an austenitic microstructure, adding hydrogen to the argon is possible to give higher heat input and an oxide-free bead.

3.5.8 Summary

Table 3.6 summarises the selection of gases for different materials.

3.6 The gas flow rate

The flow rate has an important influence on the quality of the weld metal and the surface of the weld. Too low a flow gives inadequate protection since air contaminates the gas. On the other hand, if the flow is too high, there will be turbulence when the gas exits from the nozzle, and oxygen and nitrogen are drawn into the arc. In both cases the result will be welds contaminated with oxides and nitrides, and porosity.

The selection of the right flow depends on many factors. Examples are:

- The density of the shielding gas.
- The size of the nozzle.
- The distance between nozzle and workpiece.
- The type of metal.
- The joint type and position.
- The amount of metal vapour.
- The weld parameters, e.g. spray arc, short arc.
- The velocity of surrounding air.

A recommended gas flow for argon mixtures in short-arc welding is 10–15 l/min and for spray-arc welding 15–25 l/min. For a bigger diameter of the gas nozzle the flow has to be increased. A rough rule of thumb for argon mixtures is to use the same gas flow in litres/minute as the inner diameter in mm of the gas shielding nozzle. Thus a gas nozzle with diameter 15 mm should have a gas flow of 15 l/min. Helium-containing gases require higher gas flow to protect the weld pool since helium has a low density. The flow increases the more helium is used in the mixture. This is most important for higher helium contents. Longer distance between the nozzle and the workpiece also needs higher gas flow. Aluminium requires higher gas flow than for steel.

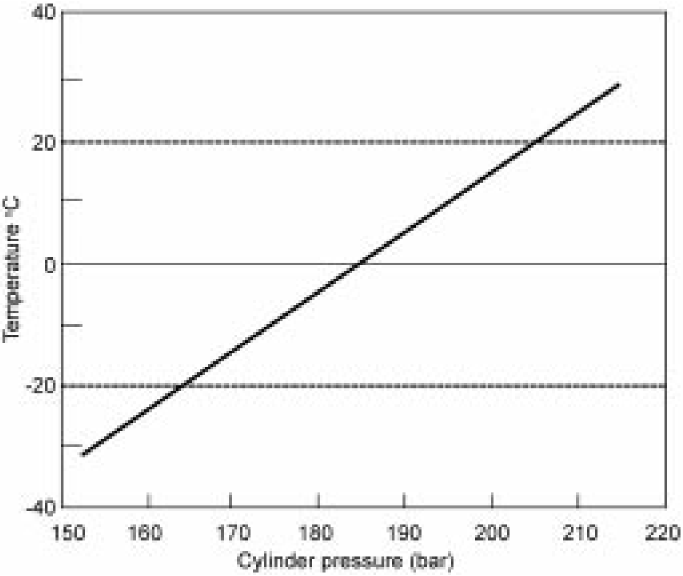
3.7 The gas supply system

The shielding gas supply must be very reliable and supply the gas at the right flow rate and quality to assure the weld quality.

3.7.1 High-pressure cylinders

The inert and reducing gases and gas mixtures in the groups M 1 and M 2 are supplied in gas cylinders compressed to a pressure of up to 300 bar. The normal pressure is 200 bar. At these pressures the gases are in a gaseous state. The inner volume of the cylinder is up to 50 litres. That means that the content of gas as referred to the conditions where it is used (1 bar and 15 ºC) is about 200 × 50 litres or 10 m^3. The actual content differs somewhat for the different gases depending on varying compressibility of the gases. The compressibility is a way of describing the divergence of the actual gas from an ideal gas. The pressure in the cylinders is referred to standard conditions. If it is 200 bar and 15 ºC specified by the gas supplier the pressure in the cylinder varies with temperature as shown in Fig. 3.5. The actual content in the cylinder is the same. When the gas is withdrawn from the cylinder through the valve and the regulator it expands and the temperature of the gas decreases. In some cases it is necessary to use a heating device in order not to get a frozen valve when flows are high and the ambient temperature is low.

CO_2 liquifies at room temperature when the pressure is increased to about 50 bar. This means that CO_2 in the cylinder at room temperature is present partly as a liquid and partly as a gas. This also explains why the cylinder content is specified in kg and not in m^3. When the gas is let out from the cylinder the pressure in the cylinder remains constant until all the liquid phase has been vapourised. The amount of remaining gas cannot be evaluated from



3.5 Cylinder pressure–temperature diagram for argon at constant cylinder content.

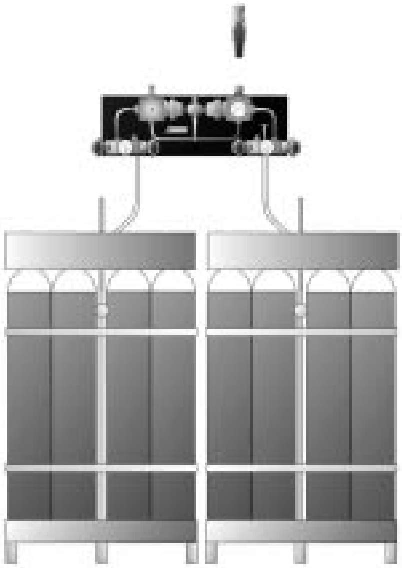
the pressure until all the liquid CO_2 is vapourised. A heater may also be necessary in this case.

For the filling of mixtures special precautions are taken by the gas supplier to get a homogeneous mixture. This is especially important for mixtures including CO_2.

The cylinders are normally made of steel. Smaller cylinders are also made of high-strength aluminium alloys. For factories needing higher amounts of gas bundles are also available. An example is a bundle with twelve cylinders. The cylinders have connections between each other and one or two valves where the gas can be emptied.

3.7.2 Central gas distribution systems

The individual cylinders are often used near to the stationary welding equipment in the workshop or in mobile working places. The use of a central distribution system can improve safety and productivity. Normally a certain number of working places and cylinders are necessary to motivate the investment. The cylinders or more often bundles are placed outside the building. A simple regulator or more advanced manifold system is used to give the pressure needed to feed the pipe system in the workshop where a number of outlets are distributed (see Fig. 3.6). At each working place the necessary flow of gas has to be controlled.



3.6 Central gas distribution system (Air Liquide).

An alternative to the use of a pure gas or a gas mixture already made by the gas supplier is to use a gas mixer. The gas mixer can be supplied either from storage tanks with gas in liquid state or combination with storage tank and bundles. Since the gas in the tank is in liquid form it must be vapourised before mixing. Storage tanks are used for high consumption of shielding gas.

The storage tanks are well-insulated pressure vessels to minimise the vapourisation that can occur depending on the heat flow into the tank. If the pressure increases there are safety valves to release the pressure. During normal conditions the regular flow of gas from the tank to the vapouriser lowers the pressure and keeps the liquid cold.

3.7.3 Control of the gas flow

A regulator is necessary to adjust the right flow of gas. The type of regulator used in MIG welding can measure the flow of gas. This is done either indirectly by regulating the pressure before a capillary hole or by a rotameter tube. In the first case the manometer has a scale in l/min directly related to the actual flow. In the second case a fixed preset pressure is used in combination with a rotameter. A knob is used to set the required gas flow.

The rotameter scale is aimed at the gases for which it is calibrated. Due to the similar flow properties of argon, CO_2 and O_2 the same regulator can be used for argon and mixtures with acceptable accuracy. If, on the other hand, helium-containing gases are used with the same regulator a correction is necessary. Helium density is about 1/10 of that of argon. If the flow of an argon–helium mixture has the same value on the argon rotameter tube, the real flow is much higher. On the other hand, since the flow of argon–helium mixtures must be higher to give the same shielding effect, it is a good approximation to use the same value as is normally used for argon mixtures on the rotameter tube and it will automatically give a higher flow rate.

3.7.4 Two-stage regulators

In the welding equipment there is normally a magnetically controlled valve, that shuts off the gas flow when the welding stops. The gas pressure is then increasing up to the output value in the regulator that can be 2 to 4 bars. When the welding starts there will be a higher flow just at the start and this gives increased gas consumption. A two-stage regulator has a lower outlet pressure and the build-up of gas will be less. How big this higher consumption is depends on the length and diameter of the hose between the regulator and the magnetic valve. This problem is most evident when many short welds are completed.

3.8 Safety in gas distribution

Most shielding gases used are not flammable and from a safety point of view are considered inert. Gases with more than 2.9% of hydrogen in argon are characterised as flammable but they are seldom used in MIG welding.

If the gases are handled correctly there are no safety problems. The general rules regarding the storage of gases, and the transport and handling of gas cylinders have to be followed. There is often national legislation for the safety of handling and transportation of gases. Since the gases in the cylinders are under high pressure it is necessary to be careful anchoring the cylinders and connecting the regulators correctly. When welding in narrow spaces the risk of oxygen deficiency must be considered.

Special considerations are necessary if central gas distribution systems are used. The cylinders, bundles, tanks and gas mixers, etc., are often placed in a room or an enclosed area outside the workshop. The equipment must be regularly looked after. High-pressure hoses may be used to connect bundles or cylinders to the manifold. The force from a high-pressure hose is very high if it is broken and the hose must be checked regularly and changed after a certain time as defined by law or by the hose supplier.

In order to get a safe and well functioning gas distribution system it is advisable to have a written maintenance programme including all measures that should be taken at certain intervals.

3.9 Developments in gases and gas distribution

The gas suppliers and research institutes continuously study the possibilities for improving the shielding gases. In this chapter the focus has been on MIG welding with one solid or flux-cored wire. Most research today is concentrated on high productivity methods mainly with two electrodes in twin or tandem configuration. It is also possible to use a single electrode with unconventional welding parameters. For the selection of gas for these methods see Chapter 8.

The newest development in welding methods is laser–hybrid welding where a laser beam and a MIG arc work together in one melt pool. The selection of gas must consider both the demands from the laser process and the MIG process.

The general trend in the selection of gases for MIG welding has been influenced by the materials used and by their thicknesses. High-strength steels are used most often. The thickness needed in the construction will be lower in many cases. The surface quality of the steels is also better and the spatter will be minimised to decrease the grinding operations. Even if the cost of CO_2 is low, its drawbacks regarding oxidation, spatter and difficulties in optimising parameters are more important. Mixtures of argon and CO_2 are therefore used more frequently. There is a trend towards higher argon contents of 90% or more. At

3.7 Integrated valve–regulator device for easier cylinder handling (Air Liquide).

the same time some CO_2 is needed to give better sidewall penetration. In thin materials the risk of lack of fusion is also lower. Minor additions of CO_2 and O_2 are also suitable for pulsed arc welding because the spray arc regime starts at lower arc currents.

Stainless steels with very high amounts of alloying elements and nickel and nickel alloys require no, or very small, additions of arc stabilising CO_2 or O_2. For the austenitic microstructures additions of helium or hydrogen can be used.

The gas cylinders have not changed very much for a long time. The use of 300 bar instead of 200 bar in the cylinders has appeared in some countries. The gas content in the cylinders increases, but special precautions need to be taken to prevent new regulators being mixed up with old regulators. The weight of the gas in the cylinder increases due to higher pressure – the higher pressure needs cylinders with higher strength which often means higher material thickness and heavier cylinders. This means that the cylinders are more difficult to handle.

Another new development is to integrate the regulator in the valve of the cylinder. The content of the cylinder is shown on a manometer all the time and the flow required can be easily adjusted. The time for handling of the cylinders is decreased and the safety is improved (see Fig. 3.7).

3.10 Bibliography

Air Liquide (1997) Handbook for TIG-, MIG- and MAG-welding (in Swedish).

Baum, L. and Fichter, V (1999) *Der Schutzgasschweisser MIG-/MAG Schweissen*, DVS-Verlag, Duesseldorf.

Lucas, W. (1992) *Choosing a shielding gas*, Welding & Metal Fabrication 6/1992.

4

Consumables in MIG welding

L-E STRIDH, ESAB AB, Sweden

4.1 Standards

Welding involves a wide variety of base materials. While it is possible to design a consumable to match more than one base material, it is easy to understand why there are so many norms and standards for particular base materials, for example governing wire electrodes used for gas shielded metal arc welding. When we look at welding globally we find a number of different standards that are specific to that region of the world. The USA, for example, uses the American Welding Society (AWS) standards. Since they were among the first, they have been adopted in other parts of the world. In Asia the Japanese JIS standards are widely used, though the equivalent Chinese standards are becoming more important given the size of the Chinese economy. To try and collect and present the various national and regional standards here would be impossible.

A better way of approaching the subject is to divide consumables into families or groups, as the various national and regional standards do. There are consumables, for example, for non-alloy and fine grain steels, high strength steels, creep resistant steels, high alloy steels, Ni-base steels, aluminium and many more. What differs between the various standards is often the minimum and/or maximum values for particular consumables. This is due to variations in research findings into metallurgical properties and, and in the case of some standards, the reliance on old data.

To illustrate the nature of the various standards, this chapter concentrates on one of the European (EN) standards for welding consumables covering wire electrodes and deposits for gas shielded metal arc welding. This standard is EN 440:1994 for non-alloy and fine grain steels.

The EN 440:1994 standard specifies consumable requirements for wire electrodes and weld deposits in the as-welded condition for gas shielded metal arc welding of non-alloyed and fine-grained steels with minimum yield strength of up to 500 N/mm^2. One wire electrode may be tested and classified with different gases. The classification of a weld deposit is based on tests of the all-weld metal. The wire electrode is classified according to its chemical

Table 4.1 Symbol for strength and elongation of all-weld metal

Symbol	Minimum yield strength (N/mm^2)	Tensile strength (N/mm^2)	Minimum elongation (%)
35	355	440–570	22
38	380	470–600	20
42	420	500–640	20
46	460	530–680	20
50	500	560–720	18

composition and mechanical properties, and the shielding gas. The classification is divided into five components:

1. The first part of the classification code is the symbol for the gas metal arc welding process: the symbol G.
2. The second symbol (shown in Table 4.1) indicates the yield strength, tensile strength and elongation.
3. The third symbol (shown in Table 4.2) indicates the temperature at which an average impact energy of 47 J is achieved. Three specimens are tested: one individual value may be lower than 47 J but not lower than 32 J. A certain temperature automatically covers any higher temperature in Table 4.2.
4. Symbol number four can either be M or C, and describes the type of shielding gas as set out in EN 439. The symbol M, for mixed gases, is used when the classification has been performed with the shielding gas EN 439 – M2, but without helium. The symbol C is used when the classification has been performed with shielding gas EN 439 – C1, carbon dioxide.
5. The fifth symbol indicates the chemical composition of the weld metal and is shown in Table 4.3; it also includes an indication of the characteristic alloying elements.

Table 4.2 Symbol for impact properties of all-weld metal

Symbol	Temperature for minimum average impact energy of 47 J (°C)
Z	No requirements
A	+20
0	0
2	−20
3	−30
4	−40
5	−50
6	−60

Table 4.3 Symbol for chemical composition of wire electrodes

Symbol	C	Si	Mn	P	S	Ni	Mo	Al	Ti + Zr
G0	*	*	*	*	*	*	*	*	*
G2Si	0.06–0.14	0.50–0.80	0.90–1.30	0.025	0.025	0.15	0.15	0.02	0.15
G3Si	0.06–0.14	0.70–1.00	1.30–1.60	0.025	0.025	0.15	0.15	0.02	0.15
G4Si	0.06–0.14	0.80–1.20	1.60–1.90	0.025	0.025	0.15	0.15	0.02	0.15
G3Si2	0.06–0.14	1.00–1.30	1.30–1.60	0.025	0.025	0.15	0.15	0.02	0.15
G2Ti	0.04–0.14	0.40–0.80	0.90–1.40	0.025	0.025	0.15	0.15	0.05–0.20	0.05–0.25
G3Ni1	0.06–0.14	0.50–0.90	1.00–1.60	0.020	0.020	0.80–1.50	0.15	0.02	0.15
G2Ni2	0.06–0.14	0.40–0.80	0.80–1.40	0.020	0.020	2.10–2.70	0.15	0.02	0.15
G2Mo	0.08–0.12	0.30–0.70	0.90–1.30	0.020	0.020	0.15	0.40–0.60	0.02	0.15
G4Mo	0.06–0.14	0.50–0.80	1.70–2.10	0.025	0.025	0.15	0.40–0.60	0.02	0.15
G2Al	0.08–0.14	0.30–0.50	0.90–1.30	0.025	0.025	0.15	0.15	0.35–0.75	0.15

* Any agreed analysis not specified in this standard.

A designation can appear as follows: EN 440 – G 46 3 M G3Si1. It can be read as follows:

EN 440 = standard number
G = wire electrode for gas metal arc welding
46 = strength and elongation
3 = impact properties
M = the shielding gas EN 439 – M2 without helium
G3Si1 = chemical composition of the weld metal.

4.2 Availability of wires for different base materials

As has already been mentioned, wires for a variety of base materials are available. Solid wires for gas metal arc welding are by far the most widely used type of consumable worldwide. Normally, it is possible to purchase solid wires for non-alloyed steels and some high alloyed grades of steel in a wide variety of retail outlets where it is also possible to purchase the most common types of shielding gas. When comparing the solid wires for gas metal arc welding to consumables for other processes, like shielded metal arc welding (SMAW) or submerged arc welding (SAW), there is a factor that complicates the production of the consumables themselves. To achieve the different chemical composition required for SMAW and SAW, it is possible to add alloying elements to cover the electrode or the flux. The right composition must be achieved in the steel mill. Variations in composition are one of the reasons why element limits vary around the world for the same type of consumable. This sometimes has an impact on how you put together your Welding Process Specification, in order not to have quality problems in the finished product.

There are many different wires, often with different names depending on the manufacturer. It is here that a standard classification system helps. All consumables must be classified and the classification must be stated in catalogues, on labels, on data sheets and all other documentation for the consumable. This is invaluable in selecting the right consumable for a standard steel. Selecting a wire for mild steel, low alloyed steel, high alloyed steel, copper alloys, nickel alloys, aluminium grades and other materials is complex since there are different selection criteria, depending on the steel type. For non-alloyed and low alloyed steels, it is common to follow the mechanical properties of the steel when selecting the consumable. For high alloyed steels it is, in most cases, the chemical analysis that decides the choice of consumable so that it matches the composition of the base material. For some high alloyed grades it is not possible to use specific matching consumables. Here the choice may be a consumable that is 'overmatching' in order to compensate for the hardenability properties of the particular grade.

4.3 Dimensions and their influence on the process

One parameter to consider when choosing the consumable is the diameter of the wire. For gas metal arc welding, wires are available in diameters from 0.6 mm up to 2.4 mm, even if 2.4 mm is seldom used. A very high welding current is needed for this diameter to have a stable arc and there are few applications. The diameter of the wire, the welding current and the resistance of the wire all influence the heat that is developed in the arc. The current used for welding is divided by the diameter of the wire to calculate the current density, A/mm^2. The higher this value is, the more energy we will develop in the arc.

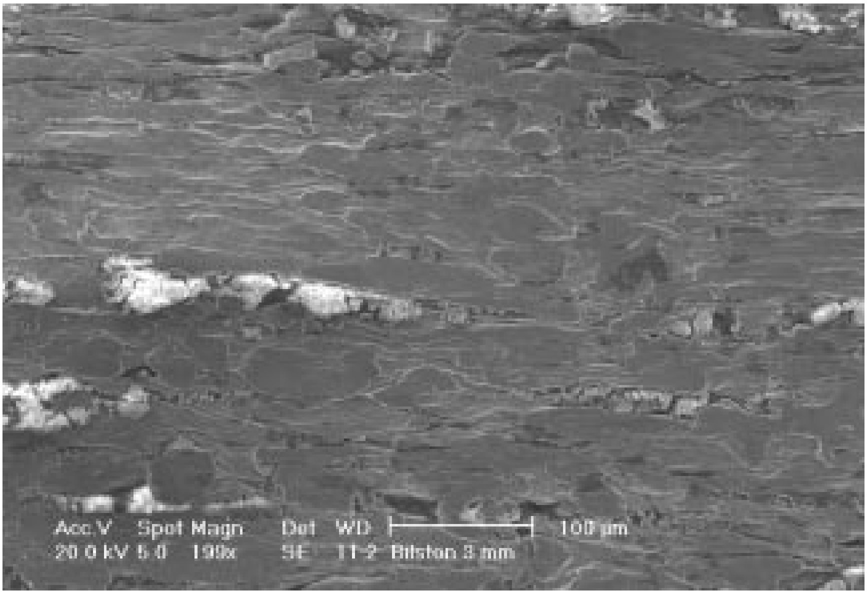
The diameter of the wire also has an effect on the diameter of the arc itself. Arc voltage, current and shielding gas also have an effect. This is an important consideration when welding thin plate. Welding thin plate is often difficult because the heat may cause burn-through and reduce the tolerance of the joint. The conventional view when welding thinner and thinner material is to reduce the diameter of the wire. This is not always the best solution. The diameter of the arc also becomes smaller. This and the relatively high current density results in a higher ‘arc force’ directed towards the plate. When this happens, the border between welding and cutting is very thin, providing little scope for maintaining joint tolerance. It is often better to use a larger diameter wire and use a power source which can pulse the current in order to control the size and frequency of the molten droplets. Pulsing the current breaks up a straight DC current so that it switches from lower to higher values in a certain frequency, reducing the total heat input to the steel, though it also causes a loss in productivity. In Table 4.4 approximate current ranges are shown for different diameters.

4.4 Consumable properties

It is very important to be aware of the properties of consumables, even apparently simple consumables such as solid wire. Welders have struggled with different problems originating from wires for many years. Experienced manual welders have built up sufficient knowledge to identify and resolve these problems. Modern production methods, however, are making increasing use of

Table 4.4 Current range for different diameters. Non-alloyed and low alloyed wires

Diameter, mm	Minimum amperes	Maximum amperes
0.6	20	120
0.8	50	180
1.2	90	400
1.6	150	475
2.4	275	550

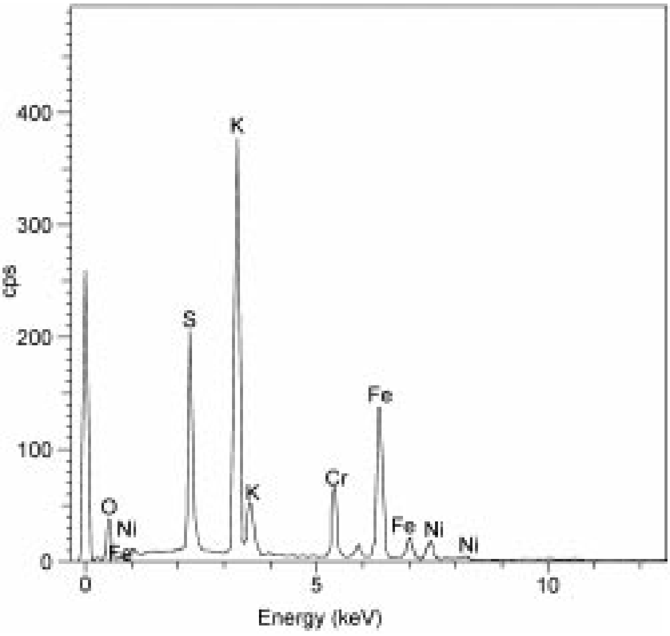


4.1 Photo of a surface with residues.

welding robots which are unable to adapt in this way, producing quality problems due to different wire properties.

The wire surface is very important since this is a major factor for the feedability of the wire (see Figs 4.1 and 4.2). Other factors affecting feedability are contact tips, liners, wire-feeders, feeder-rolls and wire-spool brakes. Mild steel wires often use copper for surface coating. The most common problem with copper coated wires is ‘flaking’ of the coating. Copper breaks up and starts to deposit in the liner and especially in the so-called ‘gooseneck’ area of the welding gun. With a sufficient deposit of copper flakes, resistance against feeding will make the wire vibrate. As a result, the arc will start to pulsate. At this moment an experienced welder will understand and correct the problem. A robot welder will run until it stops dead, the wire is burnt to the contact tip and there is a ‘snakenest’ of wire in the feeder.

Copper coating has been used on mild steel solid wires for many years. The reason for the coating is to improve the current transfer properties between contact tip and the wire. It also protects the wire from corrosion and reduces the friction between the wire and liner. More recently copper-free wires have become more popular as a way of reducing flaking and feeding problems. Copper-free wires use a special fluid to reduce friction between wire and liner and provide corrosion protection. Additional advantages are that the amount of copper in the welding fume is marginally reduced, and that the environmental impact is greatly reduced by removing the need for acid cleaning baths and copper baths.

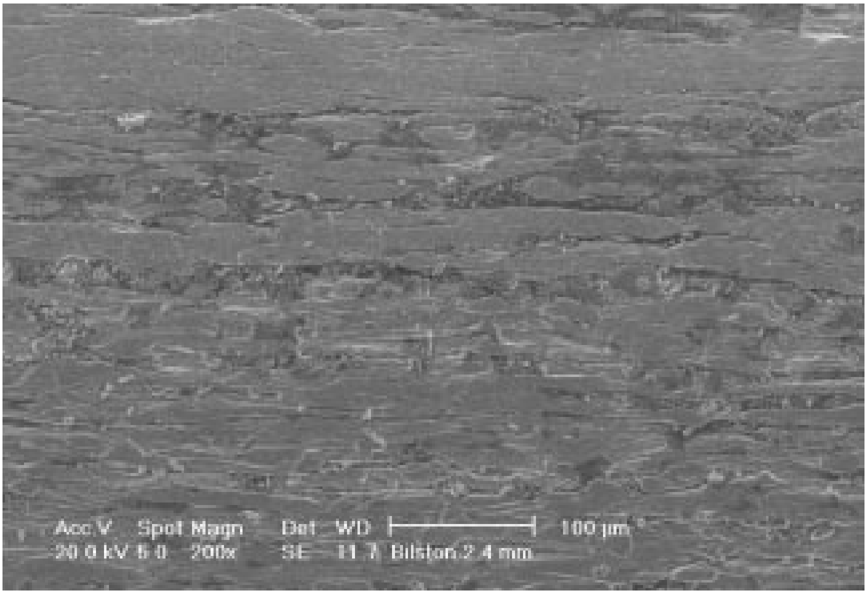


4.2 The SEM analysis of the residue.

Surfaces on stainless steel wires may either be very shiny or 'matt'. Each has advantages, depending on the application. Both matt and shiny surfaces can have a similar surface topography, the surface roughness, but still give different properties. It is when a surface starts to get rough that it starts to give problems with feeding. The rough surface will act as a file and produce microscopic grains in the liner that will deposit and cause feeding resistance (see Fig. 4.3).

Aluminium wires are very sensitive to feeding resistance since many of the aluminium grades are 'soft' and do not have the strength to overcome small feeding problems. The surface topography/roughness must be smooth. The choice of liners for feeding aluminium wires is important and there are different materials and feeding systems available on the market for this.

Welding relies on a good current transfer. Other properties that will influence this are the 'cast' and the 'helix' size of the wire. Both cast and helix are properties that are 'built' into the wire when it is produced and spooled. A mild steel wire can have a different cast and helix depending on which format it is delivered in, a 5 kg spool, a 16 kg spool or a 200 kg drum. The cast is the diameter the wire will form when a piece of wire is cut. The helix is the height to which one of the ends of a full circle rises when the other end is pushed to the floor. Cast is important in fixing the contact point in the contact tip so that current transfer is stable. The helix must not be too high. If it is, the wire has a 'twist' and the arc will start to rotate.



4.3 Photo of drawing defects on surface.

4.5 Different wire analyses and their effect on welding properties

As already mentioned, types of solid wire exist for almost all base materials. There are, of course, great differences between materials when it comes to properties like heat distribution and current conductivity, two factors that have a significant influence on welding properties. Looking at mild steel wires, for example, the presence of Si in the wire affects the wettability of the weld bead. Si influences the viscosity of the molten pool so that the edges of the pool have a very smooth transition to the base material. However, too high a level of Si will produce an excessive amount of silicon oxide (SiO_2) slag on the bead surface, because of a reaction between the millscale on most plates and the weld pool.

Stainless steels have less conductivity and heat transfer properties, and must be welded with lower heat input. The heat stays in the weld pool for longer compared to mild steel. On the one hand, this often gives good bead geometry and good fatigue properties. On the other hand, in out of position welding, the weld bead has a tendency to ‘fall out’ and become bulky and convex with bad connections to the base material.

Aluminium has good conductivity and needs high energy in the welding process. Wettability is often a problem as well as the surface appearance of the weld. Another problem for the welder is that there is no colour difference in the weld pool as it heats up, making it less easy to spot overheating and burn through. Since the melting point is low and the melting interval is short, overheating can happen quickly.

In the case of copper, conductivity and heat transfer are very good, requiring very high energy to produce good welds. In many cases it is necessary to preheat the copper plate before welding. Nickel base materials have an unusual viscosity when the metal is molten which has been likened to chewing gum. This makes it more difficult for the welder who has to be much more active with the movements of the arc in order to get the bead to ‘flow out’ and not only lie as a ‘worm’ in the joint. Angles in joint design using Ni alloys also have to be wider to allow wettability.

5

Flux cored arc welding

L-E STRIDH, ESAB AB, Sweden

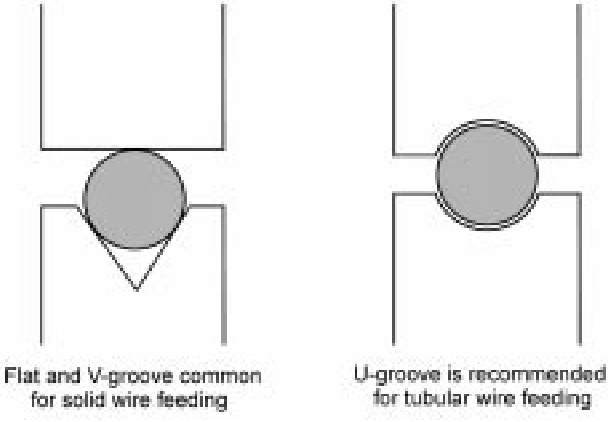
5.1 Introduction

There is very little difference between solid wire and flux cored arc (or tubular wire) welding in the process equipment used. The only real difference is that fluxed core arc welding more commonly uses a water-cooled welding gun. This is due to the fact that more heat is generated in the arc with a tubular wire used because the current density is higher with tubular wire. The typical arc types in solid wire welding (short circuit arc, globular transfer arc and spray arc) are not so pronounced or are not visible in fluxed core arc welding. Some tubular wires show only a spray arc in the current range for that particular wire, while others weld in dip transfer mode at low currents just like solid wires.

The welding process itself is a little different when seen from the welder's point of view. Arc properties and weld pool behaviour are different and require different welding techniques. The welder has more influence over the process with tubular wire welding than with solid wire welding because the contribution from the power source is higher with solid wire welding. When comparing the deposition rate between solid and tubular wire, at the same welding current and the same diameter, tubular wire welding has a higher deposition rate. It varies a little bit depending on which type of tubular wire is used, but the difference is approximately 20–30% in favour of the tubular wire.

The shape of the groove in the feeder rolls needs to be different compared with solid wire. It is common to have one flat roll and one V-groove roll for solid wire. In the case of tubular wire it is necessary to have U-shaped grooves on both rolls. This is to prevent the wire from deformation that will affect the geometry of the wire. In these circumstances the longitudinal joint may open and powder may leak in the liner (see Fig. 5.1).

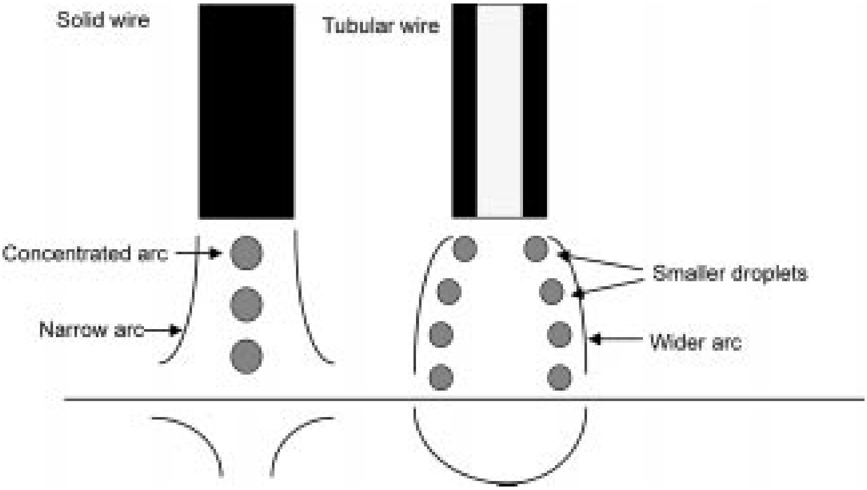
Welders need specific training in welding with tubular wires. Since productivity is higher than with solid wire, there is a larger amount of molten metal to control as well as a higher welding speed. However, control of the



5.1 Different shape of feeder rolls.

process is much easier given greater arc stability, control over the weld pool, and out of position weldability, for example. There is a fundamental difference between the spray arc from a solid wire and the spray arc from a tubular wire. It can be most easily described as the difference between a highly concentrated water jet and a concentric water jet. Therefore the penetration profile differs rather much between the processes, in such a way that the profile from the tubular wire is wider, presenting an advantage when it comes to sidewall penetration in welding a fillet weld (see Fig. 5.2).

The process uses two types of cored wires: gas-shielded wires (by far the most common type) and self-shielded wires. Self-shielded wires have chemicals



5.2 Schematic difference between solid and tubular wire arcs.

inside that produce a gas with help from the heat in the arc that protects the weld pool. These wires were originally designed to be used outdoors since a wire with an external gas shield is very sensitive to draft. This book will not discuss self-shielded wires.

5.2 EN standards for flux cored wires

Flux cored wires are also described in standards and different types have their specific standard in the same way as Ni-base and stainless steel wires. The European standard EN 758 will be described here to illustrate how standards are put together. This standard specifies the classification of tubular cored electrodes in the as-welded condition for metal arc welding with or without a gas shield using non-alloyed or fine grain steels with a minimum yield strength of up to 500 N/mm^2. One tubular cored electrode can be tested and classified with different gases. It is recognised that the operating characteristics of tubular cored electrodes can be modified by the use of pulsed current, but for the purposes of this standard, pulsed current is not used for determining the electrode classification.

The first symbol for the product is the letter T which stands for a tubular cored electrode for metal arc welding. The second symbol is for tensile properties. There are two tables for these properties because some wires are only for a single-run process and others for both single- and multi-run processes (Table 5.1a,b).

Table 5.1 (a) Tensile properties by single- and multi-run technique

Symbol	Minimum yield strength (N/mm^2)	Tensile strength (N/mm^2)	Minimum elongation (%)
35	355	440–570	22
38	380	470–600	20
42	420	500–640	20
46	460	530–680	20
50	500	560–720	18

Table 5.1 (b) Tensile properties for only single-run technique

Symbol	Minimum parent material yield strength (N/mm^2)	Minimum tensile strength of the welded joint (N/mm^2)
3T	355	470
4T	420	520
5T	500	600

Table 5.2 Symbol for impact properties of all-weld metal or welded joint

Symbol	Temperature for minimum average impact energy of 47 J (°C)
Z	No requirements
A	+20
0	0
2	−20
3	−30
4	−40
5	−50
6	−60

Table 5.3 Symbol for all-weld metal composition

Symbol	Chemical composition %		
	Mn	Ni	Mo
No symbol	2.0	–	–
Mo	1.4	–	0.3 to 0.6
MnMo	1.4 to 2.0	–	0.3 to 0.6
1Ni	1.4	0.6 to 1.2	–
1.5Ni	1.6	1.2 to 1.8	–
2Ni	1.4	1.8 to 2.6	–
3Ni	1.4	2.6 to 3.8	–
Mn1Ni	1.4 to 2.0	0.6 to 1.2	–
1NiMo	1.4	0.6 to 1.2	0.3 to 0.6
Z	Any other agreed composition		

The third symbol indicates the temperature at which an impact energy of 47 J is achieved. Three test specimens shall be tested. Only one individual value may be lower than 47 J but not lower that 32 J. When an all-weld metal or a welded joint has been classified for a certain temperature, it automatically covers any higher temperature (Table 5.2).

Symbol number four indicates the chemical composition of all-weld metal (Table 5.3). The fifth symbol indicates different types of tubular cored electrodes relative to their core composition and slag characteristics (Table 5.4).

Symbol six indicates shielding gas. The symbol M, for mixed gases, shall be used when the classification has been performed with shielding gas EN 439-M2, but without helium. The symbol C shall be used when the classification has been performed with shielding gas EN 439-C1 carbon dioxide. The symbol N shall be used for tubular cored electrodes without a gas shield.

Symbol number seven indicates the position for which the electrode is tested according to EN 1597-3:

Table 5.4 Symbol for type of core

Symbol	Characteristics	Type of weld	Shielding gas
R	Rutile, slow freezing slag	Single and multiple pass	Required
P	Rutile fast freezing slag	Single and multiple pass	Required
B	Basic	Single and multiple pass	Required
M	Metal powder	Single and multiple pass	Required
V	Rutile or basic/fluoride	Single pass	Not required
W	Basic/fluoride slow freezing slag	Single and multiple pass	Not required
Y	Basic/fluoride fast freezing slag	Single and multiple pass	Not required
Z	Other types		

1 all positions
2 all positions, except vertical down
3 flat butt weld, flat fillet weld, horizontal–vertical fillet weld
4 flat butt weld, flat fillet weld
5 vertical down and positions according to symbol 3

Symbol eight indicates the hydrogen content of the deposited metal (Table 5.5).

This is how a designation can look: EN 758-T 46 3 1Ni B M 4 H5. It can be read as follows:

EN 758 = the standard number
T = tubular cored electrode/metal arc welding
46 = tensile properties
3 = impact properties
1Ni = chemical composition
B = type of electrode core
M = mixed gases
4 = welding position
H5 = hydrogen content

Table 5.5 Symbol for hydrogen in deposited metal

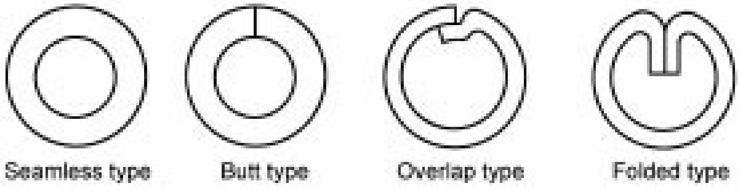
Symbol	Hydrogen content ml/100g deposited metal max
H5	5
H10	10
H15	15

5.3 Consumables

There are a number of ways to produce flux cored wires. The original method was to fill a tube, then roll and draw it to the desired size. But the most used method is to start with a metal strip on a large spool that is fed into a so-called forming line where the strip is formed between rollers. As the strip takes a U-shape the powder is filled into it and then it continues in the forming line and is finally closed. The way of closing the wire may vary depending on the production equipment and also type of wire. Butt type closings and different types of overlap closings are the most common. After this the wire goes into the drawing line where it is drawn to the right diameter either through dies or driven rolls. Wire diameters from 0.8–4.0 mm are produced. The diameters from 0.8–2.4 mm can be used for gas-shielded or self-shielded use. The larger diameters are often used for submerged arc welding.

One of the cross-sections shown in Fig. 5.3 has no visible joint. This is another way of producing the wire. Here the strip is much wider and thicker and is formed into a tube without filling it with powder. After tube forming the butt joint is laser welded or resistance welded. The tube is annealed so it becomes soft and is then spun into a spiral that is placed on a vibrating table. The powder is then poured into the tube from the top end and from the vibrations the powder fills the complete tube. Then the tube is brought into the drawing line to achieve the right diameter. There are some advantages and some disadvantages with this wire. One of the advantages is that the powder is completely protected from the atmosphere and moisture in particular. A disadvantage is that it is difficult to make the tube thin walled and therefore the wire is less productive than a thin walled wire with a joint.

There are three main types of flux cored wires with different properties: basic wires, rutile wires and metal cored wires. Basic wires have a slag that is very fluid and with a relatively low solidification temperature. The wire is difficult to use in out of position welding using a spray arc. Like solid wires, basic tubular wires can be welded in the short circuiting mode. It is therefore possible to perform out of position welding but with low productivity. The weld metal from the basic wires is of high purity and therefore can show good mechanical properties with very good impact values. For high restraint joints and root-runs a basic cored wire is recommended, since the crack resistance is high. Many basic



5.3 Different cross-sections and ways of closing.

wires perform best welded with the wire on the negative polarity. More heat is then on the melting end of the wire and less in the weld pool, improving welding properties.

It is rutile wires that have really made the use of cored wires widespread and popular. Weldability with modern rutile wires is very good. Rutile wires make it possible to weld in out of position with a very high productivity. It is common to perform vertical up welding with a productivity of 5 kg/h manually and 6 kg/h using a robot. The wires produce a more fluid slag that solidifies at a lower temperature allowing the weld bead to become flat with good wettability. The bead surface is very bright and smooth, often with a characteristic fishbone pattern. An experienced observer can look at the bead surface and identify the producer in many cases.

Metal cored wires have no slag forming elements in the filling, unlike basic and rutile types of wire where the filling is metal powder. This increases the deposition efficiency of a metal cored wire. Basic and rutile wires have a deposition efficiency between 82–88%, whilst a metal cored wire has one between 95–96%. Comparing the penetration profile from a solid wire and a metal cored wire welded on a mix gas (EN 439-M2) will show a finger-like penetration from the solid wire with a wider penetration from the metal cored wire. This makes the metal cored wire more ‘forgiving’ to a slight mistake in joint tracking. In many cases a metal cored wire of diameter 1.4 mm can be used for robotic applications in thin plate, even to 1 mm plate thickness. Joint tolerance is improved and welding speeds can increase by up to at least 30%. Metal cored wires are less appropriate for stainless thin plate due to lower heat transfer properties.

5.4 Typical applications

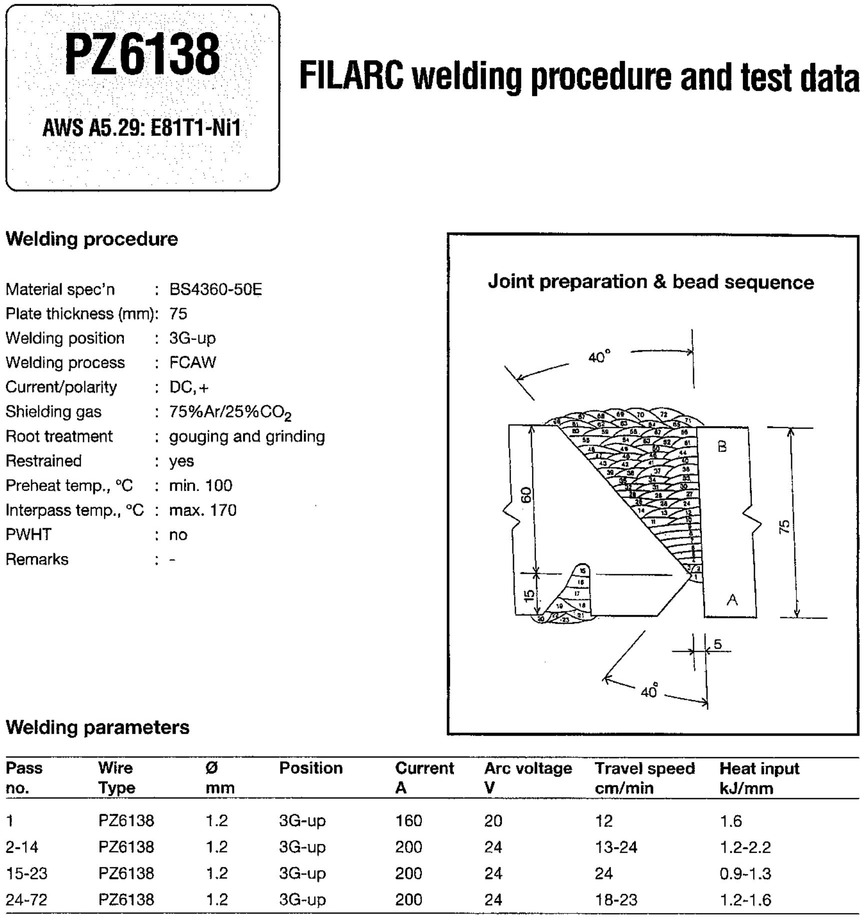
The use of flux cored wires is widespread in manufacturing, so it is difficult to highlight applications that are really typical for the process. The process is used for plate thicknesses from 1 mm up to 100 mm and over, but the main use is for plate from 5 mm up to 50 mm. Tubular wire is particularly used in out of position manual welding where productivity is much higher than with other wire types. One industry where the use of flux cored wires started rather early was the shipyards because a lot of out of position welding is required. The real benefit in this case is the increase in productivity. The deposition rate with a MMA electrode in vertical up position is about 1 kg/h. With a tubular wire a skilled welder can reach a deposition rate of 5 kg/h. In early 1980s a downhand wire was developed with the use of CO_2 shielding gas. The wire was a combination of a rutile and a basic wire and it had the advantage of resistance against porosity when welding primed plate. This led to the mechanisation of tubular wire welding within shipyards. Stations for the welding of webs to panel plate have been built with welding tractors arranged in such a way that one operator could control up to eight welding tractors at the same time. Mechanised welding originally used SAW in the panel line, but the use of tubular wires significantly reduced the cost. Some shipyards invested significantly in the use of flux cored wires in production; in some cases the use of tubular wires represented up to 75 to 80% of the total consumable consumption of the yard. More and more fillet welds were introduced in order to make it possible to mechanise more easily.

Another industry that has also used flux cored wires is the Scandinavian offshore engineering industry. In 1980–81 a number of rutile tubular wires were developed that had very good welding properties and also an alloying system that gave the weld metal very good impact properties, even down to –60 °C. Offshore yards readily used these wires and from 1983 to 1996 the consumption within this sector was huge. Quality demands within this sector remain very high. Every batch of wire is accompanied extensive quality documentation and on site CTOD tests are performed for each batch before they allowed in production. In Norway a special offshore quality standard was developed, the NORSOK standard, and this remains one of the most comprehensive standards in use (Fig. 5.4).

5.5 Choice of wires

Choosing wires is a very complex subject that would easily fill a book by itself. It is always a good idea to use manufacturers' handbooks of consumables since they often have recommendations about the correct choice. In the case of many mild steels, a major criterion is mechanical properties. In many areas, high strength steels have been used to increase service life and wear-resistance as well as reduce weight. This has led to the development of many different tubular wires to meet the requirements of these steels. Many of these wires are designed with a basic slag system in order to achieve the necessary mechanical properties. Unfortunately the basic slag system does not give the best welding properties so a great deal of effort has been put into the R&D of rutile flux cored wires and a number of rutile wires for higher strength steels now exist. In many cases it is possible to choose a standard rutile wire for higher strength steels when the joint is placed in an area where the stresses are low and will not reach the limit for a standard wire. The welding procedure will also be much simpler. A chemically matching wire for a high strength steel often requires preheating, control over interpass temperature and a controlled temperature cycle after the welding is finished.

It is important to choose the right slag system for a particular welding position. A horizontal wire requires a slag that is fluid and solidifies at a rather low temperature, allowing the weld bead to have good wettability and not to get 'bulky'. A positional wire requires a less fluid slag that solidifies at a high temperature. This creates a 'lid' on the weld pool to help shape it and to prevent the weld metal from falling down when welding vertically or overhead. There are also all-purpose wires that have a little of each property so that they can weld



PZ6138

AWS A5.29: E81T1-Ni1

FILARC welding procedure and test data

Welding procedure

Material spec'n	: BS4360-50E
Plate thickness (mm):	75
Welding position	: 3G-up
Welding process	: FCAW
Current/polarity	: DC,+
Shielding gas	: 75%Ar/25%CO_2
Root treatment	: gouging and grinding
Restrained	: yes
Preheat temp., °C	: min. 100
Interpass temp., °C	: max. 170
PWHT	: no
Remarks	: -

Joint preparation & bead sequence

Welding parameters

Pass no.	Wire Type	Ø mm	Position	Current A	Arc voltage V	Travel speed cm/min	Heat input kJ/mm
1	PZ6138	1.2	3G-up	160	20	12	1.6
2-14	PZ6138	1.2	3G-up	200	24	13-24	1.2-2.2
15-23	PZ6138	1.2	3G-up	200	24	24	0.9-1.3
24-72	PZ6138	1.2	3G-up	200	24	18-23	1.2-1.6

5.4 Example of a WPS from an offshore application.

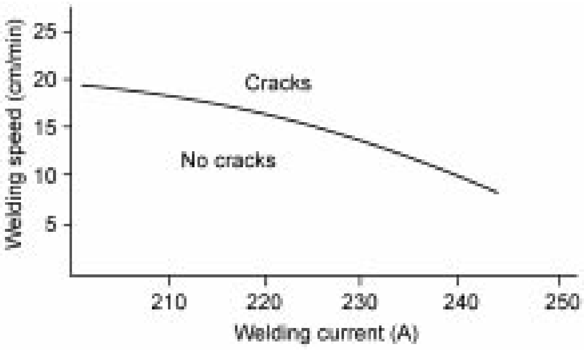
in all positions. It is not possible to get all the potential requirements into one wire. If quality demands are not too high, an all-purpose wire can be used. If there are high quality requirements, it is better to use a specialised wire.

Tubular wires for stainless steels require similar slag properties for different welding positions. Heat transfer properties are particularly important in retaining heat around the weld pool to keep it in place when welding out of position. Mo-alloyed wires require particular care. Too much Mo in the strip makes the drawing process difficult due to deformation hardening properties. Mo is therefore partly added through the powder filling. As the space inside is very limited, metallic Mo has traditionally been used. However, unmixed/unmelted Mo particles in weld can cause pitting because the melting point for metallic Mo is around 3,200 °C, well above the welding temperature. The solution has been to use ferro molybdenum instead because this has a lower melting point. However, it takes up more space inside the tube, so the design of the strip has to be considered.

5.6 Process limitations

Tubular wires have a lot of advantages in, for example, better penetration, better positional properties, arc stability and productivity. But in real life there is no such thing as the perfect consumable. The out of position properties of tubular wires have limitations, including the requirement for small beads in overhead welding. The small beads in mild steel result in low heat input and a fast cooling rate, making it difficult to control welding in an overhead position. The higher current density in the wire creates a warmer arc with higher heat radiation which creates more discomfort for the welder and the need for more rest breaks. Low fume metal cored wires increase the UV radiation from welding, bleaching clothes. It is also important to recognise other limitations such as the hot crack properties of a rutile tubular wire for horizontal welding. These wires are often used for root-pass welding on to ceramic backing and very often hot cracking of the root pass is observed. This is due to the fluidity of the weld metal, the solidification pattern, the concentration of impurities in the middle and the restraining properties. It is quite possible to use the rutile wires for this but limitations on welding current and welding speeds has to be considered to be successful (see Fig. 5.5).

There are also limitations with applications that have to be stress relieved after welding. A metal welded with rutile wires can have very good mechanical, especially impact, properties. This strength is due to micro-impurities in the matrix, such as B and Ti nitrides and carbides. However, when reaching the required temperature for stress relief, these micro-impurities tend to migrate from the grain to the grain boundaries and dissolve. This reduces the strength of the grain. In these circumstances it is better to use a wire type where the alloying system has been altered to reduce impurities. These wires have often the two letters SR attached to the product name, standing for stress relief.



5.5 Parameter limitations, hot crack in root.

6

Pulsed MIG welding

K WEMAN, Wemab AB, Sweden

6.1 Introduction

Pulsed MIG welding, or pulsed arc MIG welding, is a method of welding that uses current pulses from the power source to control transfer of the droplets of molten filler material in the arc in such a way as to produce a stable and spatter-free arc, even with low welding data. The method was developed in the 1960s by J.C. Needham at TWI in the UK. However, it was very expensive at that time to produce power sources that were sufficiently fast. As a result, the first power sources used part of the sine wave for creating their pulses, which meant that the pulse frequencies could be varied only in fixed steps.

It was not until the inverter power source was developed at the end of the 1970s that pulsed MIG welding became more feasible. However, even so, it was the introduction of digital process control that has really made the method widely accessible. The technology used is referred to as ‘synergic pulsed MIG welding’, with the word ‘synergy’ indicating a method of facilitating setting up the equipment by enabling the power source automatically to select appropriate pulse parameters. As the welder increases or decreases the wire feed speed, the other parameters are adjusted in order to maintain a suitable arc.

Thermal pulsing (low frequency pulsing) is a standard process for TIG welding. This is a way to achieve improved control of the welding pool and reduce the sensitivity for joint variations. It is possible to use the same advantages at MIG welding by pulsing the wire feed speed.

Some new advanced MIG equipment is able to use thermal pulsing with the pulsed MIG process, i.e. the slow thermal pulses are superimposed on the higher frequency drop transfer pulses.

AC pulsed MIG is a method where pulsed MIG welding is combined with AC current. This process gives a better gap tolerance and lower residual stresses and deformation thanks to a lower heat input.

Tandem MIG welding uses two wires that are fed into the same molten pool. When the process is used in pulsed transfer mode the two power sources are synchronised such that their pulses are out of phase with each other. That means that simultaneous pulses are avoided and the risk of undesirable magnetic interaction between the arcs is reduced.

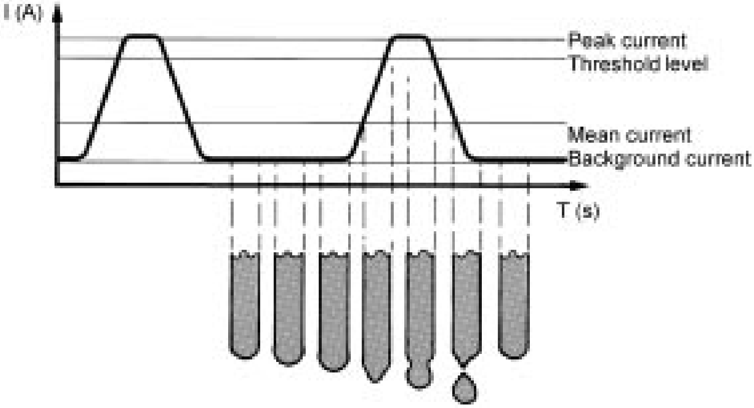
6.2 Process principles

6.2.1 Pulsed MIG welding

Power sources with improved dynamic control of welding current have been available during recent decades. That makes it possible to use pulsed transfer. The current periodically alternates between a high and a low current level and permits the metal to transfer during the high current pulse in spray transfer mode, but with a lower overall heat input than spray (see Fig. 6.1). A microprocessor control system calculates the pulse parameters needed for the actual choice of electrode size, material type and shielding gas and the pulse frequency needed to keep the arc length constant.

Pulses from the power source pinch off the drops from the electrode at the same speed as the electrode is fed. Therefore it is possible to avoid short circuits and spatter generation. While short arc welding is normally the most suitable method for thin sheet carbon steels, pulsed MIG is often the best choice for stainless steels or aluminium.

The pulses serve two purposes: supplying heat to melt the filler wire, and also to pinch off just one molten droplet for each pulse. This means that, as the wire feed speed increases, the pulse frequency must also increase. This will result in keeping the droplet volume constant at all times. A low background current contains the arc between the pulses. Although the current amplitude in each pulse is high, the average current – and thus the heat input to the joint – can be kept low.



6.1 Pulsed MIG welding has controlled drop transfer at a mean current much lower than the threshold level for spray arc.

The stable and controlled drop transfer with pulsed MIG allows the use of an increased wire diameter. This is often utilised in aluminium welding where the wire is difficult to feed because of its softness.

The method allows welding with much lower heat input than is possible with spray arc welding. That permits welding in position and in thin materials. However, the greater heat input, relative to that of short arc welding, reduces the maximum usable wire feed speed, thus allowing a lower production speed.

Pulsed MIG welding restricts the choice of shielding gases. As with spray arc welding, the CO_2 concentration of an argon/CO_2 mixture must not be too high: the usual 80/20% gas mixture, as used for short arc welding, represents the limiting value.

Advantages with pulsed MIG welding are:

- The process is fully controlled and spatter-free.
- The ability to extend spray arc welding down to lower welding data is particularly suitable when welding materials such as stainless steel or aluminium. It becomes possible to weld thin materials, or to perform positional welding, with better results than would be obtained with short arc welding.
- Pulsed MIG welding is sometimes used within the normal spray arc range in order to provide better penetration into the material.
- A larger wire diameter can be used: that will be less expensive and easier to feed.
- Research work has shown that the efficient droplet pinch-off reduces overheating of the droplets, resulting in less fume production.

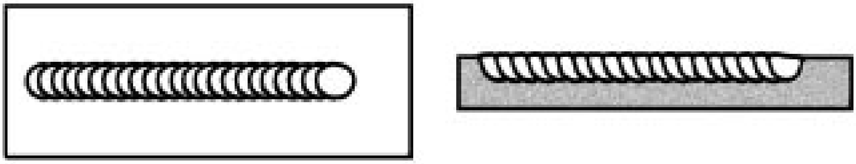
Applications

Pulsed MIG welding has most applications in the range of aluminium and stainless steel. As it offers very stable operation in the low current range it is an appreciated alternative to short arc welding. Short arc is a colder process and should preferably be avoided for aluminium welding.

6.2.2 Thermal pulsing

The low frequency pulsing generally used with TIG welding is called thermal pulsing in order to distinguish it from the higher frequency pulsed drop transfer process used at MIG welding.

Thermal pulsing is used to achieve improved control over the weld pool. When used for MIG welding the wire feed speed is pulsed with a frequency in the range 1–10 Hz. The process involves heating a point on the workpiece until the metal is completely molten. The welding current is then reduced, such that much of the weld pool solidifies, after which the process is repeated as the arc is



6.2 Thermal pulsing.

moved along the joint. The overlapping weld ripple creates a pattern (see Fig. 6.2), that sometimes is desirable as a styling effect.

The pulse current is higher than would normally be used for continuous welding. Supplying heat in this way, at a high rate but for a short time, makes more efficient use of the energy. This has a number of benefits:

- Less sensitivity to gap width variations.
- Better control of the weld pool during positional welding.
- Better control of penetration and the penetration profile.
- Reduced sensitivity to varying heat dissipation between joint faces.

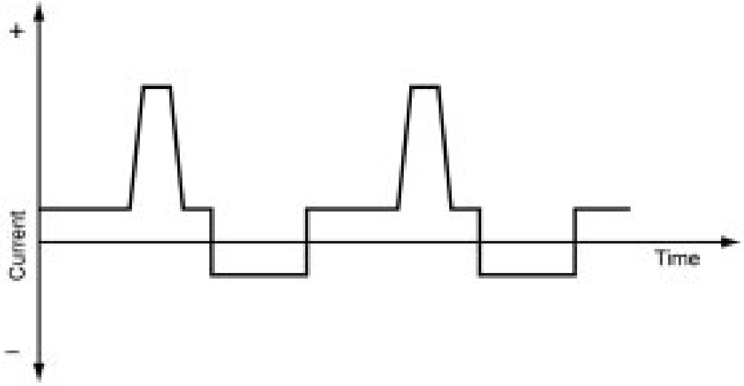
Thermal pulsing with short arc welding makes it possible to weld thinner materials and with wider weld bead and decreased wetting angle at the weld toe than would otherwise be possible. Note, however, that the pulse current must be higher than would be the case during continuous welding if optimum results are to be achieved.

Combining thermal pulsing with the high frequency pulsed drop transfer is used for aluminium welding and as a result gives the TIG-like pattern. Another possibility is to combine different process types in the pulse and during the background time.

- Pulsed MIG during the high current period and the short arc settings during background time make it possible to weld very thin aluminium or stainless material. If the background time is not too long this can often be done without any drop transfer taking place between the pulses.
- High current spray arc combined with low current pulsed MIG is suitable for positional welding in thicker materials.

6.2.3 AC pulsed MIG welding

Pulsed drop transfer is often used together with AC MIG welding. Figure 6.3 shows a typical current waveform. The pulses are normally on the positive part of the cycle as this facilitates drop transfer. The electrode negative (EN) proportion of current tends to increase the deposition rate and reduce the heat input, see also Section 1.11 about AC MIG welding.



6.3 AC pulsed MIG current waveform.

6.2.4 Tandem MIG welding

Tandem MIG welding is used to increase welding speed and productivity by using double wires in the same pool. Each of the two wires is separately connected to its own power source. Stability problems may occur as the wires must operate close together and are exposed to magnetic interaction. By using pulsed current and synchronising the two power sources, such an overlap is avoided, the interaction will be minimised and process stability will be improved.

6.3 Equipment and control technique

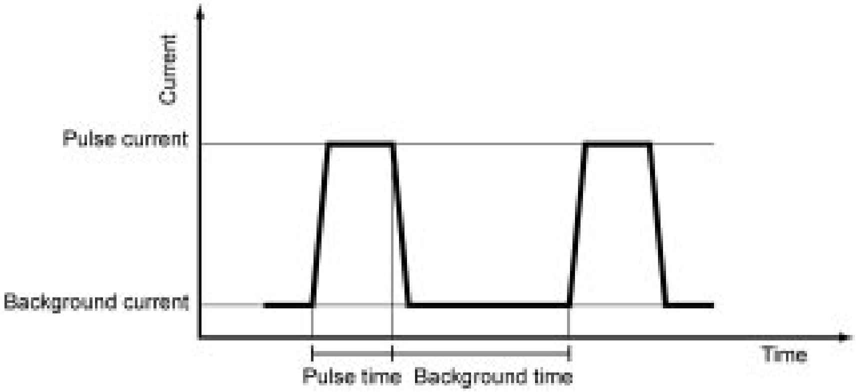
6.3.1 Power sources

Inverter power sources dominate today at pulsed MIG welding. They are able to control current output fast enough to create the desirable pulsed waveform. The use of pulsed welding techniques has become much more available thanks to the inverter. Thyristor power sources or thyristor add-on units used to be the only available equipment for pulsed MIG and these were much more primitive in operation.

Advanced inverter equipment incorporates a fast feedback control of current and voltage. The wire feeder normally also has a feedback control of the motor speed.

6.3.2 Pulse parameters

In principle, the four underlying parameters of pulse current value, background current value, pulse time and background time are required in order to define the pulse parameters (see Fig. 6.4). However, the background time may be replaced



6.4 Naming the pulse parameters.

by the pulse frequency. In addition, the rise and fall flanks of the current pulse can be given a slope. This affects the welding noise. A steep slope produces more noise. On the other hand, excessive slope can, in the worst case, affect the ability of the pulse to pinch off the droplet.

6.3.3 Synergy lines

A synergy line helps the welder to choose appropriate settings of the welding equipment. Suitable welding parameters are pre-programmed into the equipment. By selection of the correct filler wire material, shielding gas and wire diameter, the control unit will automatically set the optimum voltage and all pulse parameters that have been tested and selected for this particular combination, and as suited to the wire feed speed that has been set. Changing the wire feed speed automatically adjusts all the other settings. The relationship between the feed speed and the other parameters is referred to as the synergy line.

6.3.4 Basic conditions for correct operation of pulsed MIG welding

Two important conditions must be fulfilled if the process is to be stable. One is that the pinch-off force must be that required to pinch off one droplet per pulse, and the other must be that the current is that required to melt the filler wire at the correct rate so that the arc length is maintained constant.

Pinching off the droplet

During the current pulse, the droplet is subjected to a downward force, which is used to pinch off the droplet. However, surface tension tends to keep the droplet in contact with the wire. In order to break the droplet away from the wire, the force acting on it must be applied for a sufficient time. Simplified, this can be expressed as:

$$\text{Force} \times \text{Pulse time} = \text{Constant}$$

i.e. a higher value of pulsed current means that the time can be reduced. The force acting on the droplet is proportional to the square of the current, which means that we can say:

$$I_p{}^n \times t = D$$

where n is close to 2, I_p is the pulse current and D is a constant that depends on wire size, shielding gas and wire material. As an example, Ponomarev and Slivinsky (2003) mention a D-value of 400–500 for a low carbon 1.2 mm wire and Ar + 5%CO_2 as shielding gas. This formula is perhaps not exactly correct, but it does show that the current has a greater effect than does the time.

With all parameters correctly set, the droplet will be pinched off immediately after the pulse ceases, see Fig. 6.1, without forming any spatter.

Melting the filler wire

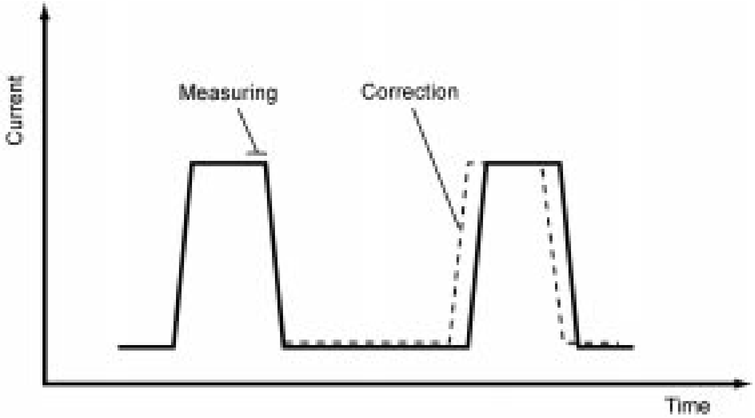
It has been explained in Chapter 2 that, if the arc length is to regulate itself, the power source must have a constant voltage characteristic. However, this risks conflicting with the requirement of being able to control the pulse parameters at the same time. Ideally, we would like to be able to control both the pulse current and the background current (i.e. constant current control), but this would then put self-correction of the arc length at risk. Different manufacturers of welding equipment have solved this problem in different ways.

One way is to maintain constant voltage of the pulse and a constant value of background current, sometimes referred to as CVCC (Constant Voltage and Constant Current) control. The pulse current will then vary, depending on whether the arc length is long or short.

Another alternative is to do the opposite, i.e. CCCV, which means that it is the background current that is varied.

These operating principles restore control of the arc length, although to some extent at the cost of control of the pulse parameters.

There is a possible solution to this problem, enabling both arc length correction and control of the pulse parameters to be used together. This involves a CCCC characteristic, i.e. constant current during both the pulse and the background current period between pulses. The arc voltage is measured at the end of the current pulse, thus providing a signal to indicate the arc length. If the arc is too short, the pulse frequency is increased, which is done in practice by maintaining the pulse width but reducing the background current duration (Fig. 6.5). This method of control makes it possible to fulfil the conditions necessary



6.5 The arc voltage is measured at the end of the pulse, and the background current duration changed if necessary (ESAB).

to pinch off each droplet (the pulse current and duration remain the same), while at the same time controlling the arc length.

The constant current control during the background current period ensures that the arc will not extinguish at the lowest current settings.

6.4 Bibliography

ESAB, *Pulsed MIG welding*. Order no XA00104420. (http://www.esab.com/kcentre/files/PulsMigEn.pdf)

IIW Doc. XII-1629-00. *Improve Sheet Metal Welding Quality & Productivity with AC Pulsed MIG Welding System*. Daihen Corporation, Japan.

IIW Doc. XII-1720-02. *MIG-welding of very thin Al-sheets by AC pulsed current*. SLV München.

Mulligan, S.J. (2003) *Pulsed MIG arc welding processes for joining thin sheet aluminium*. TWI Cambridge.

Ponomarev, V. and Slivinsky, A. (2003) *Welding arc and MIG/MAG welding transfer*, Kiev.

7
MIG brazing

G LINDÉN, Air Liquide Gas AB, Sweden

7.1 Introduction

There has been an increasing interest in the use of arc brazing especially for joining of zinc coated steels with low thickness up to about 3 mm. Zinc coatings are used to improve the corrosion resistance of the steel. Most applications are found in the automotive industry for body components. Owing to the high heat input of arc welding there are frequently problems with spatter and porosity connected to zinc melting and evaporation. Zinc has a melting temperature of about 420 °C and vapourises at about 900 °C. This is much lower than the melting point of steel at about 1400 °C. There is also high deformation of the parts during and after welding. One possible way of solving these problems is to use arc brazing that uses lower temperatures for joining. The method is very similar to arc welding with high productivity and the possibility to robotise. The same type of welding equipment can also be used.

In arc brazing the brazing material is melted in an electric arc that also heats the base material. Both MIG, TIG or plasma processes can be used. A similar method is laser brazing where a laser beam melts the brazing material and heats the parent metal. The MIG brazing is the most common method in automotive applications. Robotised MIG brazing is efficient with high speed and good quality. Since the shielding gases can be either inert or with some additions of active gases it is more correct to use the name MIG/MAG brazing but for convenience MIG brazing is used in this chapter.

In this chapter the process will be described as well as the brazing materials, the shielding gases and the necessary equipment. The joint types and the process parameters are discussed. The quality of the joints is very important and measures to assure the quality are also summarised.

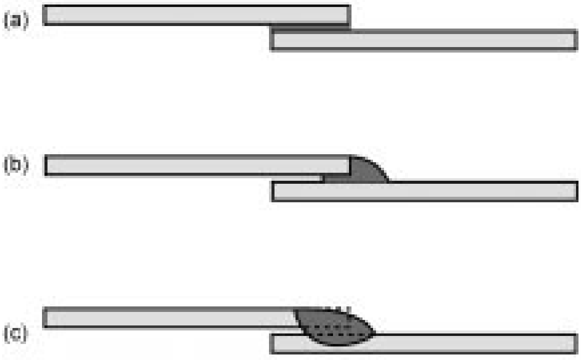
7.2 Process principles

For brazing the filler metal has a lower melting point than the base material and the base material is not melted. The joint is formed by heating of the base material to the melting temperature of the brazing material that flows over the surfaces to be joined. Good wetting is necessary to get a satisfactory joint. This is normally achieved by a flux cleaning the metal surface. The strength of the brazed joint is dependent on the strength of the brazing material and is lower than a welded one. Normally the brazing utilises a joint with a very small gap. The distance between the joint faces are some tenths of a millimetre. The capillary action working on the melted brazing material facilitates the flow over the entire joint surfaces. The brazed joint is formed by local diffusion between brazing material and base material before and during the solidification. Flames, induction or similar techniques are used for heating.

Arc brazing differs from capillary brazing by using another joint configuration. The difference is shown in Fig. 7.1. In the arc-brazed joint it is not possible to rely on the capillary action to give a joint with a high strength mainly due to the small bonding area between the sheets. There is the same type of bonding between the brazing material and the base metal but the geometry is different. The inherent strength of the brazing material plays a more important role.

Figure 7.1(c) also shows the MIG weld where both parts are melted together with the filler metal and form the weld. A higher heat input is needed compared to brazing.

The brazed joints may be fillet joints, often between overlapping sheets. In arc brazing the heat is more concentrated than in capillary brazing and more similar to welding. The high temperature from the arc and the concentrated heat source leads to some melting of the base material near to the arc root. The dilution must be minimised since it can influence the strength negatively. On the other hand too low a heat gives bad joints owing to insufficient wetting. The heat must also be minimised to get lower deformations and to save the zinc layer as much as possible on both sides of the sheet. The zinc layer surrounding the joint on the upper plate gives cathodic protection of the small areas that have lost the zinc layer during brazing.



7.1 Brazed and welded joints: (a) capillary brazing, (b) arc brazing, (c) welding.

For MIG brazing the same type of equipment is used as for MIG welding. The electrical characteristic of the power source is the same.

MIG brazing also differs from MIG welding by the use of a copper-based filler material. Its melting point is much lower than a normal filler material for MIG welding. A shielding gas must be used to protect the process from the influence from air during brazing but also to improve the process stability and to give a smooth surface of the joint.

As the heat input shall be kept to a minimum the short arc transfer or pulsed arc transfer modes are used. A low heat input means low evaporation of zinc and small influence on the base material. Short arc transfer gives some spatter. Pulsed arc has the advantage of lowering the spatter, but the heat input is somewhat higher. The material transfer is easy to control and the gap bridging is good for fillets in overlap joints. The bead surfaces will also be flatter than with short arc.

The joints used are the same as for MIG welding but butt joints are not recommended. Fillets in overlap joints are common. The gaps must be kept low to facilitate the brazing. With too wide and varying gaps the throat thickness also varies.

7.3 Base materials and filler materials

MIG brazing is used for uncoated steel and steel coated with metallic coatings. Most important applications are for zinc coated steels with a maximum sheet thickness of 3 mm. For steels with higher strength or thickness it is important to notice that the strength of the brazed joint is considerably lower than that of the steel. The zinc layer should be a maximum of about 15 μm. High coating thickness may cause problems and the joining speed will be reduced. To get a high quality joint the steel surface must be clean from oil, dirt, etc.

The filler materials used are copper-based alloys with low amounts of silicon, aluminium, manganese, nickel, tin, etc. These filler metals have a high ductility that is important in dynamically loaded structures. No brittle compounds should appear within the joint or in the bonding zone. The melting range ought to be small to avoid hot cracking. A summary of the properties of the most common filler materials is given in Table 7.1. Both $CuSi_3$ and $CuAl_8$ have a

Table 7.1 Common copper-based brazing materials for MIG brazing

Brazing material		Alloy content	Melting range (°C)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
Silicon bronze	$CuSi_3$	3% Si	910–1025	250	380	46
Aluminium bronze	$CuAl_8$	8% Al	1030–1040	180	380–450	40

microstructure with one phase only and the melting range is fairly small, which is an advantage in the solidification process.

Aluminised steel needs aluminium-containing fillers. Brass (Cu-Zn) is not suitable because of the evaporation of zinc.

The filler materials are supplied in wires typically between 0.8 and 1.6 mm in diameter. A hard wire is easier to feed in the wire feeder.

7.4 Shielding gases

In MIG brazing the shielding gas will protect the process and the material from the surrounding air. Argon, argon–helium or argon mixtures with minor additions of active gases are used. The most suitable gas mixture depends on the actual conditions and must be evaluated in the individual case.

Compared to pure argon small additions of oxygen (1–2%) or carbon dioxide (2–3%) stabilises the arc and lowers the spatter for zinc coated steels. The porosity also decreases. This is especially true for $CuSi_3$ brazing material. For $CuAl_8$ brazing material helium additions are used to increase the heat input. Higher heat input means that the brazing material will flow more easily but may on the other hand give less control of the melt pool. The width of the arc will be bigger and not so concentrated in the middle of the arc as with pure argon.

Minor hydrogen addition also increases the speed since a higher voltage is needed and this gives more heat. Hydrogen reduces the oxides on the bead surface and gives a smooth bead. The risk of porosity increases.

Special gas mixtures can be used which combine the effects of the different gases in the gas mixture.

7.5 Equipment

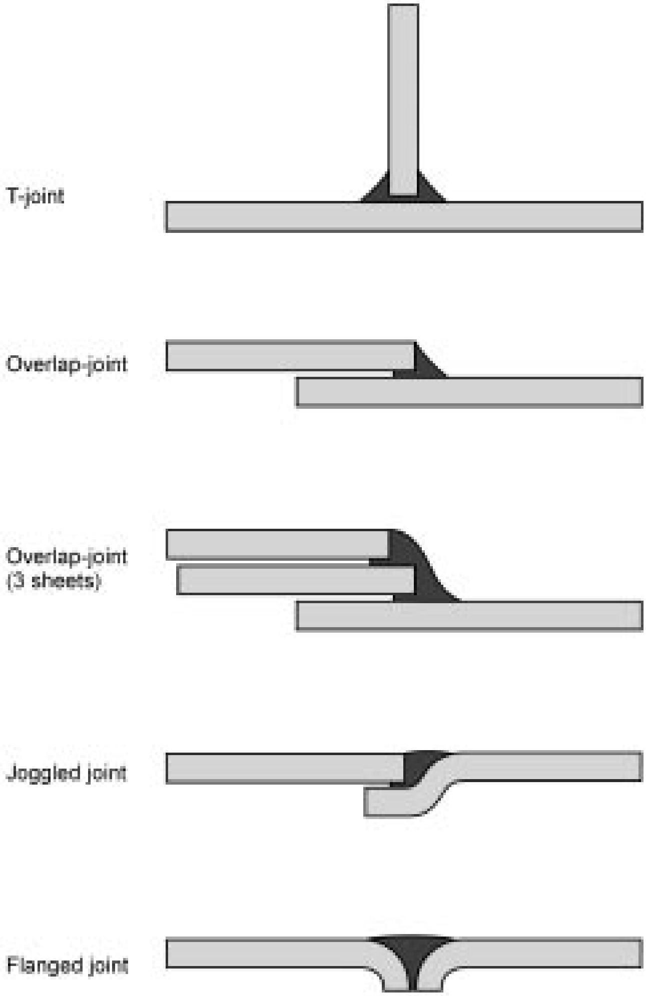
The power sources necessary for MIG brazing are the same as for MIG welding. For pulsing technique there should be a low background current with good stability. High power is not necessary. Some manufacturers supply special synergy lines for the brazing materials normally used.

The wire feeder must be able to feed softer wires than normally used for steel and with good stability of the wire feed rate. Four-roll drive systems with semicircular groove rolls are recommended. If the hose package is long a second wire feeder may be necessary.

The hose package shall have an inner liner made of Teflon or plastic-graphite. The soft wire will otherwise be worn.

7.6 Brazing technique and brazed joints

Typical joint configurations are shown in Fig. 7.2. The strength of the brazed joint is the weakest point of either the brazing material, the diffusion zone

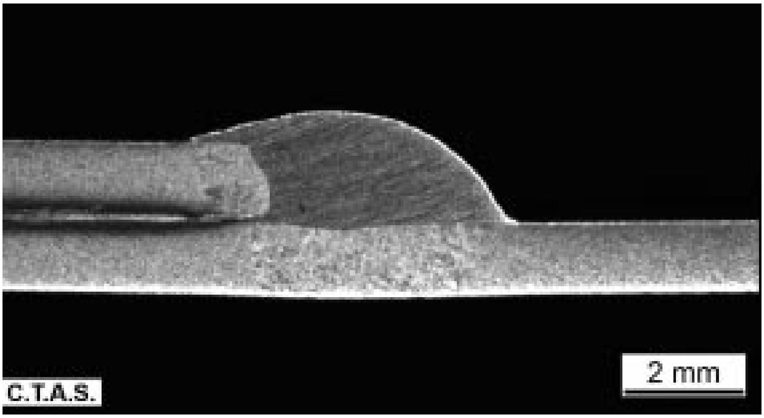


7.2 Some joint configurations for MIG brazing.

formed by good wetting between the sheets or the sheet itself. The penetration between the sheets in overlapping sheets cannot be used in the strength calculations. The fracture in tests of the joints in unalloyed low-strength steels normally occurs in the sheet material. This means that the joint is stronger than the sheet in the actual configuration. For high-strength steels tests must always be done to check the critical part of the joint.

Brazing in sheets with high residual tensile stresses should be avoided because of the risk of brazing brittleness. In these cases the copper alloy may penetrate along the grain boundaries of the base metal.

A typical brazed joint is shown in Fig. 7.3. The melting of the sheet material



7.3 Typical brazed joint in an overlap configuration. Filler material Cu 3% Si, wire feed rate 5 m/min, 100 A, 13.7 V and MIG-brazing velocity 10 mm/s (Air Liquide).

is fairly small. The gap is also small. The zinc vapour has had the possibility to escape and no pores are seen. With the fairly low heating the zinc layer on the opposite side has not been severely damaged.

Since the temperature of the arc is very high, there is a risk that some parts of the sheets may be heated and melted. If there is high demand on brazing speed, the filler wire speed is increased and the heat input may locally be too high. The melted iron may dissolve in the joint. If the iron content in the brazed metal is too high it may lower to the strength of the joint. The local variation of the iron content within the joint can also be big and for certain mechanical tests, e.g. the peel test with considerable bending forces, the strength can be low due to higher local brittleness. Cu-3% Si brazing material seems to be more sensitive to this effect than Cu-8% Al. The heat input must be optimised, which means that the melting of the base metal is minimised at the same time as the joining between base metal and braze material is assured.

The torch position is important. In forehand torch position of zinc coated sheets the zinc layer is preheated and vapourised before the droplets of filler material reaches the melt pool. By the heat from the droplets most of the zinc disappears. Some of the zinc can also dissolve in the filler material. The degassing time for zinc vapour must also be sufficient. Otherwise this can give porosity.

7.7 Conclusion

The advantages with MIG brazing compared to MIG welding are:

- Reduced amount of spatter that leads to reduced post-welding operations such as grinding.

- Low heat input means low deformation.
- Good mechanical properties of the joint, in most cases better than the neighbouring sheets.
- The good corrosion behaviour of the coated sheets is retained since the coating is not severely damaged.
- The joining with large gaps is simpler than with welding.
- The risk for burn-through is reduced in very thin sheets.

Limitations may be:

- Mechanical strength may be lower is specific cases.
- The price of the brazing material is considerably higher than the normal MIG welding electrode.

7.8 Future trends

MIG brazing has recently become more popular in the automotive industry. It seems likely that other industry segments for high production series in thin sheet will also find the method interesting. The coated steels are used more often also in smaller thickness and higher strength. More advanced coatings combined with heat treatment of the sheet material require joining methods with lower heat input. At the same time the wetting between brazing material and the sheet material must be improved. This needs development in filler materials as well as in shielding gases.

7.9 Bibliography

Anon (2000) *Lichtbogenlöten – Grundlagen, Verfahren, Anforderungen an die Anlagentechnik*, Merkblatt DVS 938-1 Duesseldorf.

Knopp, N. and Killing, R. (2003, 2004) *Hartlöten verzinkter Feinbleche mit dem Lichtbogen – sicher und Wirtschaftlich*, Der Praktiker 12/2003, 1/2004 Duesseldorf.

Oehman, E (2003) *Properties of MIG/MAG-brazed joints in zinc-coated steel sheets*, IM-2003-109 Swedish Institute of Metals Research, Stockholm.

8

Improving productivity in MIG/MAG methods

J HEDEGÅRD, Corrosion & Metals Research Institute, Sweden

8.1 Introduction

In this chapter, methods that enable MIG/MAG welding with increased productivity are presented. Advantages and disadvantages with the processes are discussed and process selection aspects are commented upon.

High productive arc welding is basically an adaptation of a standard method to achieve a higher production rate. The improvement can be utilised either as an increase in welding speed or as a higher deposition rate. For the welding of thin sheet materials, methods that allow an increased welding speed are the main interest, while the welding of thicker materials is preferably carried out with high deposition or deep penetration welding methods. The applications are mainly mechanised or robotised welding. Manual welding is generally not suitable owing to the difficulties in managing a stable high welding speed or in withstanding the heat generated from the higher welding currents. One exception where manual welding can be performed should, however, be mentioned: it is cored wire welding. Still, a mechanised cored wire welding solution will reach higher productivity.

High speed welding (HSW) is a term that has been used in articles for the past 20 years when progress was made and somewhat faster welding was made possible. It is therefore necessary to define the actual method and productivity range when high speed welding is discussed. At present, HSW with MIG/MAG is performed with travel speeds between 1 and 6 m/min. Factors influencing the possible increase in productivity are: the material type and thickness, the welding position, quality demands on the welded joint, and the welding equipment used.

High speed welding can be achieved with the following MIG/MAG (related) methods:

- TIME.
- Rapid processing.
- The LINFAST concept.
- High-speed cored wires.

- Double wire welding: twin or tandem wire welding.
- Hybrid welding: laser–MIG/MAG.

The first four of these processes are single wire welding methods. All of these utilise the beneficial effect of an increased stick-out (in this chapter defined as the electrode to workpiece distance). Here, although higher wire feed speeds are used, the welding current is maintained at a level still suitable for welding by increasing the stick-out (i.e. preventing the arc pressure from reaching too high a level). Special shielding gases are in some cases used to enable an improved arc stability or to promote a certain arc type or a deeper weld penetration. When cored wires are used, the higher electrical resistance in the wire will also help to prevent the welding current from reaching too high values at high wire feed speeds.

In the cases of double wire welding and laser–MIG/MAG welding, the beneficial effects of combining two processes are used. For double wire, twin or tandem, the required amount of filler metal for the joint can be distributed over two wires and two arcs. This results in, for each wire, a lower wire feed speed and a lower arc pressure than for the single wire welding case with the same (total) productivity. Therefore, these double wire processes can reach a higher productivity. The arc pressure is distributed over a larger area which enables higher weld data settings before weld defects or other process limits occur.

For laser–MIG/MAG welding, apart from a distribution of the required energy over two processes, the laser beam and the MIG/MAG welding arc have a stabilising effect on the other process. New combinations of process settings can be used here and a higher degree of process optimisation is made possible. All these processes are further discussed below (see Section 8.3).

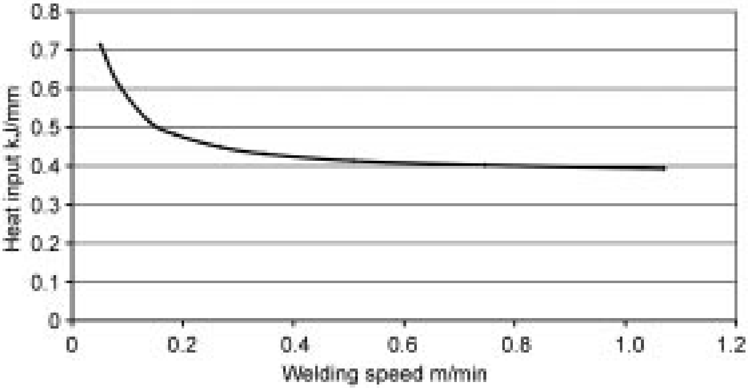
Before discussing the high productive arc welding methods more thoroughly, some short comments on the influence of an increased welding speed (travel speed) on the thermal losses and the required heat input are given.

8.2 Basics for high productive arc welding

8.2.1 Influence of welding speed on thermal losses

In general, if an increased welding speed can be used, this will lead to reduced thermal losses into the base material due to a reduced cooling effect. This results in a better thermal efficiency for the welding process. Therefore, to a certain extent, a lower heat input can be accepted when the travel speed is increased (Lundin *et al.* 1997a). See Fig. 8.1 where the graph represents the calculated required heat input [*q*] as a function of the travel speed for performing a fillet weld with weld size 4 mm in C-Mn steel with 6 mm material thickness. Note: the calculation is made with a simplified model, but it shows the beneficial influence of an increased welding speed.

Limiting factors for how much the welding speed can be increased are: the possibility of maintaining the welding gun position along the joint (avoid



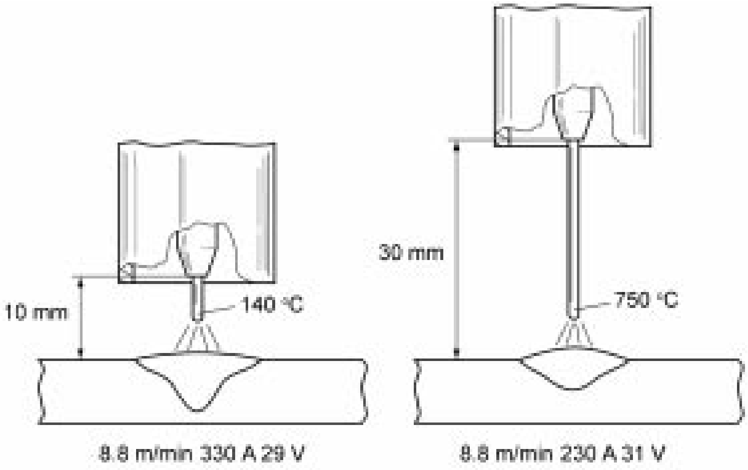
8.1 Required heat input [q] vs travel speed for performing a single V-joint in 4 mm C-Mn steel. (Weman and Pekkari 2004).

misaligned weldment) and the occurrence of weld defects such as undercut or humping weld bead. The limits are dependent on both equipment and application and should be evaluated for each case through welding trials.

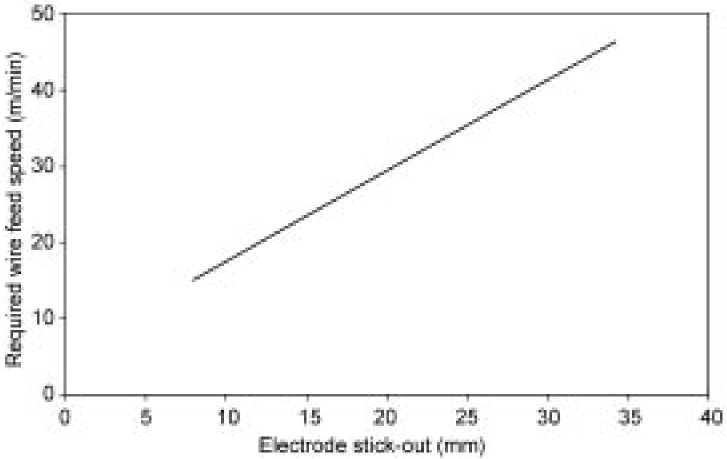
8.2.2 Influence of an increased electrode stick-out

Many methods for high productive MIG/MAG welding utilise an increased electrode stick-out. There are two reasons for this:

- It enables higher wire feed speeds since the welding current, through an increased stick-out, can be maintained at a level still suitable for welding. The principle is illustrated in Figs 8.2 and 8.3. The arc pressure (i.e. welding current)



8.2 The temperature in the electrode extension due to the resistive heat, illustrated for two different stick-out levels.



8.3 Required wire feed speed to maintain 400 A welding current when the electrode stick-out is increased (computer simulation) (Weman and Hedegård 1998).

must not reach too high a level, otherwise the process boundary will be reached with a humping weld bead or a cutting arc as a result. With an increased wire feed speed, the current will increase but if the stick-out is also increased at the same time, the current can be maintained in the same region as before.

- The electrode extension is preheated more when an increased stick-out is used (see Fig. 8.2). This enables a more rapid melt-off of the electrode tip and also a reduced energy requirement for this (compared to the case with a shorter stick-out).

The electrode stick-out level is often set between 20–30 mm for high-speed welding, sometimes more. Limiting factors when selecting a suitable electrode stick-out level are: the risk of a misaligned weldment (increases with an increased stick-out) and the risk of a reduced gas shielding of the weld pool. The gas shielding can in many cases be compensated for by using an increased gas flow, sometimes combined with a larger gas cup.

Finally, it should be noted that an increased stick-out is mainly used for high productive welding of steel (both C-Mn steel and stainless steel). It is less efficient for aluminium welding due to the lower resistance in the filler materials.

8.2.3 Increased productivity – a combination of welding speed, stick-out level and wire feed speed parameters

Setting out from an assumed welding process start point, with selected levels for wire feed speed, stick-out and welding speed; a certain weld size is achieved. From this process setting, the wire feed speed is first increased. This results in a higher welding current and a larger weld size, the latter since more material is added per weld length. If the increased welding current is combined with a step-by-step increased stick-out level, it is possible to create a situation where the welding current is reduced back to the same region as before, but still with more filler material added compared to the original setting. So the weld size will still be larger – unless the travel speed is also increased. If these three parameters are increased and balanced well, it is possible to perform the same weld size and weld geometry as in the original case, but with a higher welding speed.

An illustration of this ‘balance of three parameters’ is shown in Fig. 8.3. Here, the required wire feed speed to maintain a 400 A welding current has been calculated when the electrode stick-out level is increased. The increase in stick-out will cause a reduced welding current if no compensating action is taken. In this case, a compensation by increased wire feed speed was taken to maintain the welding current at the same level (here: 400 A). From this graph, we can, for example, see that a 400 A welding current can be achieved with 20 m/min wire feed speed and a stick-out of 14 mm, but also when using 30 m/min wire feed speed and a 22 mm stick-out. The latter case will have a 50 per cent higher welding speed (for the same weld size).

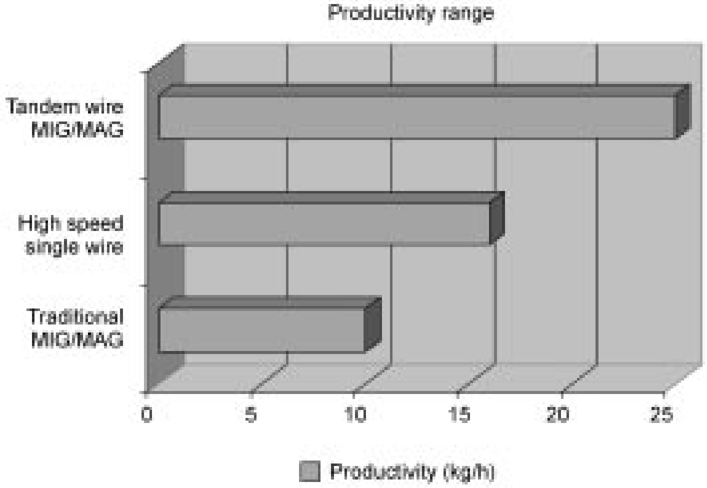
8.3 Methods for increased productivity with single wire

In this chapter, high productive methods for single wire welding are described. The methods are:

- TIME.
- Rapid processing.
- The LINFAST concept.
- High-speed cored wires.

A short historical background is also given on the development of the methods. Note: these high productive single wire methods have often been developed by different companies and can be seen as ‘concepts’ rather than different welding processes. In some cases, there are strong similarities between the concepts, in other cases not. All of these methods should, however, be included in the general definitions of the MIG/MAG welding process.

A comparison of the traditional MIG/MAG and the high productive methods is given in Fig. 8.4. Please note that the achievable productivity level for a certain method is not a definite number, it will differ very much depending on the application. Therefore, the figures in the diagram should only be seen as approximates.



8.4 High productive MIG/MAG single wire welding methods, a principal diagram.

8.3.1 Discovering the arc types

During the development of the high productive MIG/MAG welding methods in the 1980s, some special arc types were focused on: the ‘free flight’, or ‘moderated’ spray arc, the rotating (spray) arc and the forced short arc. Most of these arc types were, however, discovered long before. When MIG/MAG welding was developed in the 1950s, the arc types of the process were explored. In an American patent from 1959 (Lesnewich 1959), all spray arc types are mentioned – including the rotating (spray) arc. The benefits of the high-current spray arcs are discussed in this patent application, especially the rotating arc. The same author also wrote an important paper in this area: (Lesnewich 1958) ‘Control of melting rate and metal transfer in gas-shielded metal arc welding’.

Many of the developed high productive single wire welding concepts use these spray arcs and are therefore quite similar in the general description, but they differ in the selection of the shielding gas used and to some extent also in the welding parameter range and settings used. They focus on promoting certain weld penetration profiles, or enabling or avoiding arc rotation.

One novelty from the 1980s during the development of the high-productive MIG/MAG welding methods was, however, the forced short arc: how it should be set and used.

8.3.2 The TIME method

The ‘TIME process’, as it is called, was invented by John Church in the 1960s. The abbreviation stands for Transferred Ionised Molten Energy. Although the method was invented long ago, it was not introduced successfully to the market until the 1990s. The reason for this was that a higher degree of maturity was needed for the equipment. To make full use of the method, stable wire feeding speeds up to 50 m/min were required. Inverter power sources should also be used to secure a fast and precise adjustment of the welding current (West *et al.* 1991).

TIME is a high speed MIG/MAG welding process (Halmoy *et al.* 1991). The central part of the concept is characterised by Church (1989) and Church and Imaizumi (1990):

- The use of spray arc with free flight axial metal transfer droplets. The transfer takes place totally within the plasma arc column. This is promoted by a special shielding gas: (65% Ar, 26.5% He, 8% CO_2, 0.5% O_2).
- Solid wires with 0.8–1.6 mm diameter are used with up to 50 m/min wire feed speed. The deposition rate is higher, or much higher, than for conventional MIG/MAG welding.

In early work concerning the TIME method the rotating spray arc was not promoted. The focus was set on a non-rotating spray arc with a concentrated plasma column, which results in a deep penetration profile for the weldment.

In later documents, however, the versatility of the process is discussed and the possibility to use the equipment for different purposes and different arc types is highlighted. In some papers, the operational range is divided in three groups: (West *et al.* 1991).

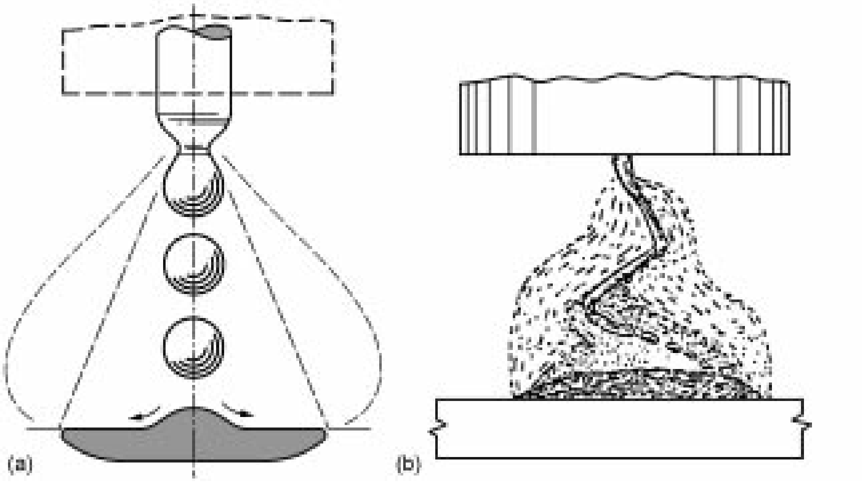
1. Conventional short arc, up to approximately 8 m/min wire feed speed.
2. Axial free flight transfer, up to approximately 25 m/min wire feed speed.
3. Rotating arc, starting at approximately 30 m/min wire feed speed.

A more cost efficient three component shielding gas has also been developed. This gas consists of 60% Ar, 30% He, 10% CO_2. The shielding gas composition has a large influence on the process areas for the different arc types (Trube and Ladi 1995). Arc rotation, for instance, is claimed to be promoted better with a gas composition with 72% Ar, 25% He, 3% O_2.

The axial free flight transfer and the rotating arc are illustrated in Fig. 8.5. The penetration profile of the weldment will be deep and often needle-like or finger shaped for the axial free flight transfer, while the rotating arc will have a more shallow penetration but often with a wider and better weld transition in the weld toe region. The metal droplets in the axial free flight transfer have a larger size than the droplets occurring with conventional spray arc. In the rotating arc, the metal is transferred in the form of a rotating stream of molten metal.

8.3.3 Rapid processing

'Rapid processing' is a concept launched by AGA in the early 1990s that comprises high-productive single wire welding with solid wire. Here, both a



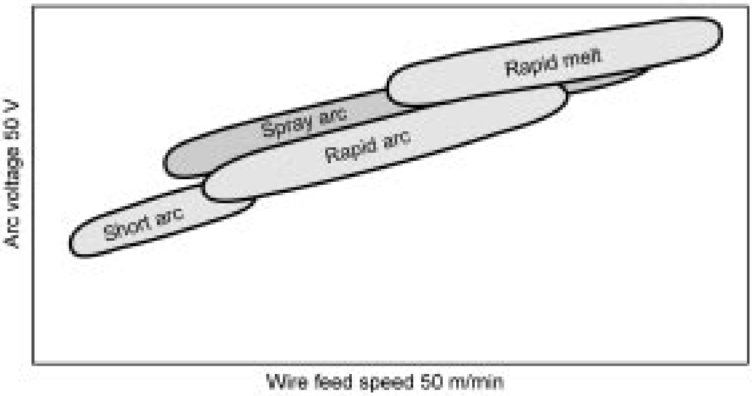
8.5 The axial free flight transfer (left (Church 1989)) and the rotating arc (right (Lesnewich (1959)).

forced short arc and high productive spray arcs are used. The forced short arc, initially called 'rapid arc', meant a new contribution to high productive welding. Here, a short arc with high welding current and high wire feed speed was introduced for the first time. Its process range is increased by a beneficial combination of welding parameters. The spray arcs used in the concept are the axial free flight spray, called moderated spray, and the rotating spray, called 'rapid melt'. The spray arcs used are the same as in the TIME concept. A difference lies, however, in the shielding gas used. For all rapid processing arc types, a more cost-efficient shielding gas with the main composition 92% Ar and 8% CO_2 is used. The concept is illustrated in Fig. 8.6 and the methods are described separately below.

Rapid arc – forced short arc

The forced short arc was initially called 'rapid arc'. More recently, this name has not been used. A forced short arc is achieved by using a reduced welding voltage. The low voltage combined with a high wire feed speed and welding current results in a high penetration (forced) short arc with a high frequency, approximately 150–400 Hz. The arc has a sharper sound than a conventional short arc. The relatively low welding voltage enables a faster welding speed without undercut. At the same time, the risk for a large weld reinforcement (due to the low voltage) is limited by a certain combination of the welding parameters. An argon-based (92% Ar, 8% CO_2) shielding gas is used with a higher gas flow than normal (20 l/min).

The process was developed for welding smaller weld sizes with high travel



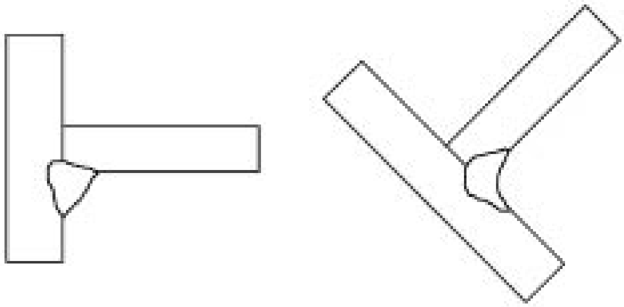
8.6 The working range of the 'rapid processing' concept is illustrated here. As a reference, the process areas for conventional short arc and spray arc are also shown. The forced short arc was formerly called 'rapid arc'. Below, the 'rapid melt' region is the moderated high current spray arc (this area is situated behind the others in the figure) (Hedegård *et al.* 1997).

speeds. Thin sheet and medium thick steels (up to 12 mm) are suitable to weld with rapid arc since the heat input is low, but with maintained fusion capacity (lower thermal losses to the material due to the high travel speed). Mechanised welding is necessary to make full use of the process. The long electrode extension requires an automated system with good repeatability to ensure a high weld quality. The welding position also has an important role; high quality weldments are best made in position PA*, i.e. horizontal position (this is an essential aspect for all high productive MIG/MAG welding methods – gravity has a large influence).

Solid wires with diameters between 0.8 and 1.2 mm are used and deposition rates between 8 and 18 kg/h can be achieved. An interesting aspect of this method is that normal welding equipment can be used, i.e. no large investments are necessary. A higher productivity can be reached by changing the process parameters. A reliable wire feeding system capable of wire feed speeds up to 30 m/min will, however, increase the productivity further. Such a system is preferable to use, as well as a water-cooled welding gun with a large gas nozzle. Also, a wire straightening device mounted somewhere in the wire feeding system will enable a larger increase of the stick-out than is otherwise possible. It will improve the accuracy of the weld positioning along the joint by reducing side movements of the wire tip in the electrode extension.

---

* PA is one of the weld positions (PA, PB, PC, PD, etc.) and refers to different orientation of the weld/joint.



8.7 Typical weld penetration profiles for rapid processing; left: forced short arc; right: rotating arc (Hedegård and Weman 1997).

Rapid melt and moderated spray arc

'Rapid melt' is intended to increase the productivity by increasing the deposition rate. Solid wire with diameters between 1.0 and 1.2 mm are used and deposition rates slightly above 20 kg/h can be achieved when welding in the best position, PA. Large weld sizes and thicker plates up to 20 mm are feasible. The spray arcs used are the same as in the TIME concept, but a difference lies in the shielding gas. For all rapid processing arc types, a more cost efficient shielding gas with the main composition 92% Ar and 8% CO_2 is used. The gas flow is higher than normal, often 20–30 l/min. A large electrode stick-out is used and a wire straightening device in the wire feeding system will increase the accuracy of the weld positioning. The welding equipment should have a current capacity of at least 600 A and a stepless voltage control. High speed wire feeding up to 50 m/min is used and stability of the wire feeding is the key to a stable process.

The spray arcs used are the axial free flight spray, called moderated spray, and the rotating spray, called 'rapid melt'. The latter occurs at higher voltage. The penetration of the moderated spray arc is often deep and finger shaped. That demands a high precision in positioning and tolerances of the workpiece. The rotating arc shows a broad penetration profile and a smooth surface transition in the weld toe region (between weld reinforcement and base material). The penetration depth will, however, decrease compared to the moderated spray.

The stability of the rotating arcs has been discussed. If the frequency of the rotation is unstable, a risk of unwanted spatter and porosity due to turbulence around the weld pool can occur. Also, in between the stable rotating arc region and the moderated spray (axial free flight) region, there is a less suitable mixed arc region. Therefore, it is important to select stable welding parameters, not too close to the arc region boundary. For this reason, to promote stable rotation (or suppress rotation) special shielding gases have been developed – this is the basis for other high-speed welding concepts with the spray arcs. Another way to control the arc stability is through a suitable selection of power source characteristics (Halmoy 1979).

8.3.4 The LINFAST concept

The LINFAST concept was developed after the TIME and the rapid processing techniques. In the LINFAST concept, advantages and disadvantages in the earlier concepts are discussed and some improvements are suggested. It is stated that mainly in the 20–30 m/min wire feed region, different arc and penetration instabilities can occur if no action is taken. The problems that may arise for the axial free flight spray are: lack of penetration in the weld root due to a too narrow weld penetration, and for the rotating arc: unstable rotation or periodic short circuiting due to the settings. It is declared that the main reason for the instabilities is too narrow a process range in this region – the arc type regions are situated too close and therefore a mixing of arc modes may occur during welding (Trube 1997).

The LINFAST concept suggests a solution to these problems by using different shielding gases depending on the selected wire feed speed and the wanted arc type. By combining suitable welding parameters with suitable shielding gases, optimised productivity and weld penetration geometry are achieved.

A higher CO_2 content in the gas increases the axial free flight spray arc region and a specially developed shielding gas will improve both the working range and the stability of the rotating arc. The shielding gas suitable for the rotating arc consists of 72% Ar, 25% He, 3% O_2. It is also claimed to give spatter-free welding and reduced slag on the weld surface.

8.3.5 High-speed cored wire

Flux cored and metal cored wires have been on the market for a long time. There is, however, a continuous development and improvement of these filler materials.

One of the improvements is the high-speed (HS) cored wire. In principle, this is an extra thin-walled wire with a high degree of filling that enables an increased deposition rate compared to other cored wires. This is made possible by a higher current density in the current carrying part of the wire (a thinner steel wall). HS cored wires can in some cases reach the same productivity as the high productive single wire welding methods with solid wire. Criteria for ‘which is the winning process’ are not only the deposition rate, but the possibility of meeting the required weld quality and weld geometry at a certain productivity level.

Dilthey *et al.* (1996), found that flux cored wires can be used with high wire feed speeds; up to 45 m/min was evaluated with stable process results. The material transport for the assessed wires was spray arc without rotation (axial free flight). The authors highlighted that more work was needed, however, to reduce the slag amounts encountered in the weldments. An adaptation of the chemical composition of the cored wire may therefore be required for achieving good mechanical properties in high speed welded joints. The shielding gas selection is also of great importance in optimising the properties in the welded joints according to Dilthey.

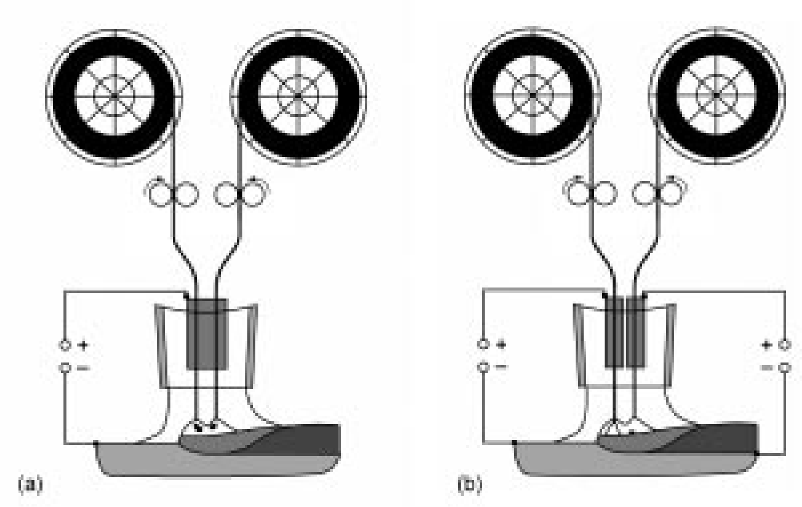
8.4 Double wire welding

Multiple wires have been used for a long time as a technique for increasing the productivity for submerged arc welding, but the principle was not implemented successfully in the MIG/MAG process until the 1990s. This was caused by technical problems of achieving a stable welding process (arc instability, arc deflection and spatter). Computer and inverter power source technology managed, however, to overcome the main problems and double wire MIG/MAG welding became possible. It allows a remarkably increased welding speed for steel, stainless steel and aluminium. Thinner materials can be welded at high travel speeds and up to 6 m/min have been reported (lap joint, approximately 2 mm material thickness). In the literature, a rule of thumb for the increase in productivity is stated as 'double wire – double speed', or 'double wire – double deposition rate'. This is not always correct, but in an application survey, the increase in productivity compared to normal single wire welding was between 50 and 300% depending on the application (Hedegård and Lundin 2001).

Double wire MIG/MAG welding utilises normal sized wires and does not require the same high wire feed speed as a highly productive single wire process. This is due to the fact that the required amount of filler metal for the joint can be distributed over two wires and two arcs. This results in, for each wire, a lower wire feed speed and a lower arc pressure than for the single wire welding case with the same productivity. Therefore, double wire MIG/MAG can reach a higher productivity since the arc pressure is distributed over a larger area which enables higher weld data settings before process limits occur. Solid wires are more commonly used, but research studies have shown interesting results when a combination of solid and cored wires was used (Dilthey *et al.* 1998a). Argon-rich gases are used as shielding gases.

The necessary welding equipment often consists of double wire feeder units with a welding gun for dual wires, and in many cases also an advanced computer controlled system. The latter enables synchronised pulsed welding or wires fed at different speeds, i.e. a root run and a cover run can be performed at the same time.

The term double wire MIG/MAG welding contains, in fact, two methods: twin and tandem welding. The differences between the methods are characterised by a different electrical set-up and wire arrangement. The arrangement of the wires can either be as twin arc (two wires fed through one torch with partially, or fully, shared arc and one weld pool) or tandem arc (two wires fed through one torch with two separated arcs and one weld pool) (see Fig. 8.8). These methods are described below in more detail.

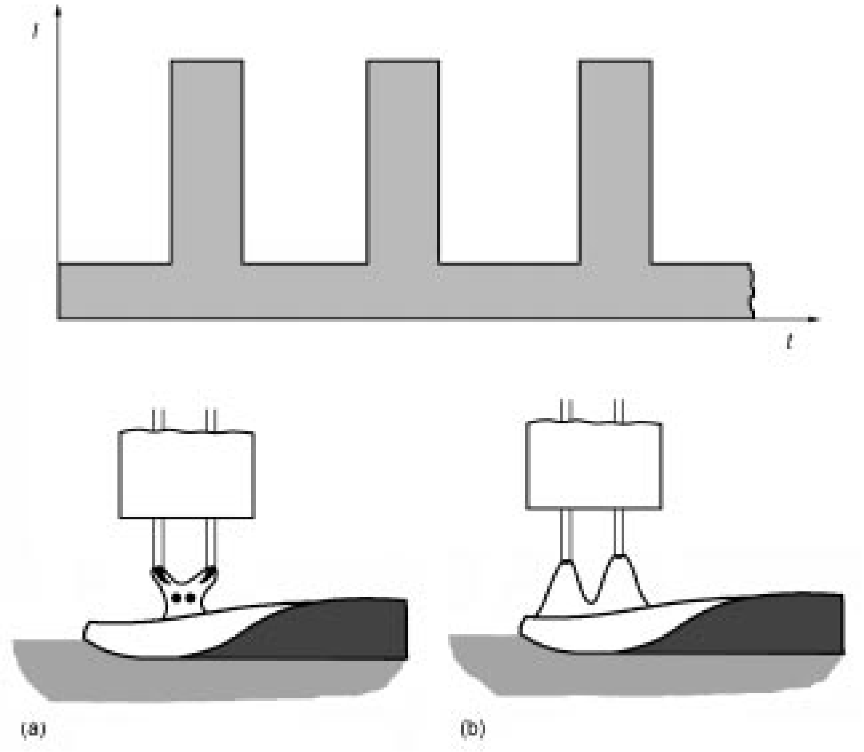


8.8 Twin wire welding (left) and tandem wire welding (right). In the twin wire set-up, the two electrodes use the same contact tip/electric potential. In a tandem set-up, the electrodes are electrically insulated wherefore more independent process settings can be used.

8.4.1 Twin wire

For twin arc, one or two power sources can be used. Since both electrodes are fed through the same contact tip and thereby also use the same welding voltage, the only reason for having two power sources is when the required max welding current so demands. There is also the possibility of using one or two wire feeding units in the system. If the same wire feed speed and wire diameter should be used for both wires, only one feeder is required (with dual-track feeding rollers). For the more advanced twin arc welding systems with computer controlled supervision, two wire feeding units are used to enable different wire feed speeds and, when applicable, different wire diameters. The possibility of using different wire feed speeds is limited, however, owing to the fact that the electrodes use the same welding voltage. A difference of up to 8 m/min in wire feed speed is theoretically made possible in some computer controlled twin arc welding systems.

The distance between the electrodes in the welding gun is relatively small. This has the advantage that the size of the welding gun is often not much larger than the single wire welding gun. On the other hand, the disadvantage with this solution is that the arcs will be very close to each other and there is an increased risk of arc disturbances and spatter. The close launch of two welding arcs, for instance with pulse peaks at the same time, often results in the formation of one mutual arc due to the arc attraction. The arcs will be partially, or fully, shared and one mutual weld pool is created (see Fig. 8.9).



8.9 An illustration of pulsed welding with twin arc. The arcs will attract, resulting in a partly or fully shared arc.

The material transport is best performed with spray arcs, or pulsed spray arcs. It is not possible to use short arc with a stable result. The spray arc droplets will for some weld settings join (mutual arc) in flight and form larger drops. In other cases, the drops will have free flight to the workpiece but hit the weld pool in the same position, or very close. The selected electrode stick-out level and the wire angles in the welding gun also have a strong influence in this matter. The electrodes are often fed through the contact tip with an angle so the electrodes are pointing slightly towards each other coming through the gun.

The distance in between the electrodes ‘contact point’ measured on the workpiece, for a selected stick-out level, is called the electrode inter-distance. Typical electrode inter-distances for twin arc MIG/MAG welding systems are 4–8 mm. This is a short distance compared to the tandem welding systems, and therefore arc deflection and spatter are more frequently a problem for the twin arc systems. Also, for systems with electrodes angled towards each other, the electrode stick-out level will need to be limited in order to reduce the arc deflection problems (i.e. too small electrode inter-distances). The same situation is present for the tandem systems but much less accentuated. From a historical viewpoint, the twin arc systems for MIG/MAG welding were developed before the tandem arc systems.

Typical applications today for the twin arc are:

- When the demand for reachability is high, i.e. a small welding gun is essential.
- Thinner joints that can be welded with dual in-phase pulsed arc.
- Thicker materials that can be welded with double spray arc.

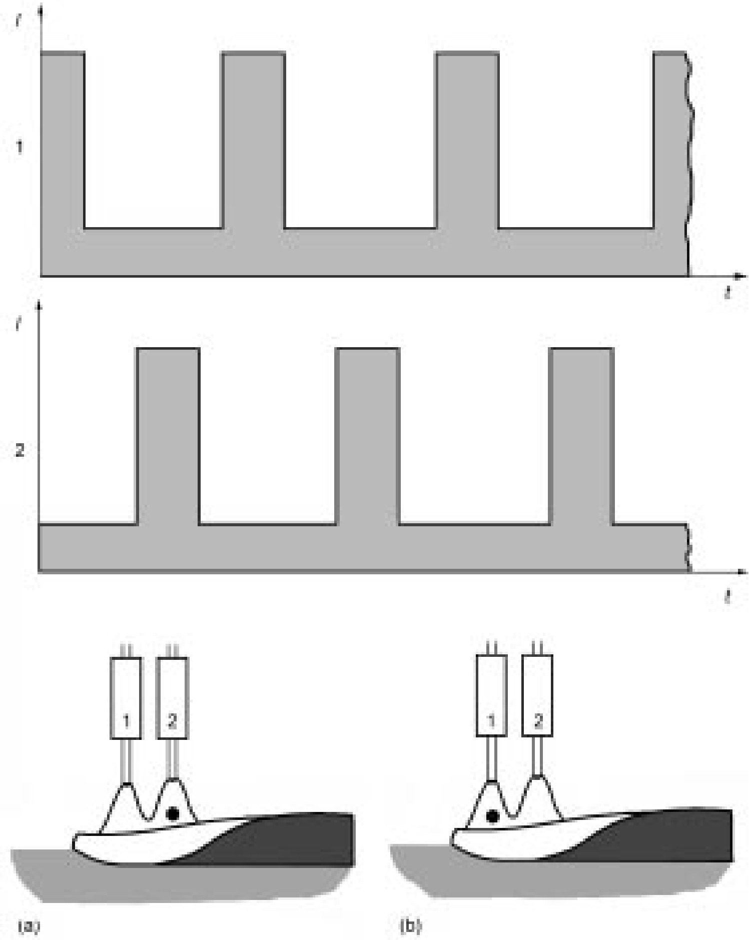
8.4.2 Tandem wire

With tandem arc, the electrodes are electrically insulated from each other so fully independent process settings can be used. This enables quite different process approaches to be evaluated. For example, electrodes of different types or diameters can be used as wire no. 1 and no. 2, different arc types and wire feed speeds can be used on the electrodes, etc. It also means, however, that the parametric evaluations increase, which makes development of weld data more time consuming. After an initial learning period, this becomes less of a problem since standard approaches for different joint types can be found. These approaches do, however, depend on the equipment used and are therefore only briefly commented on here.

The tandem system comprises two power sources and two feeder units. In most cases, the welding will result in two separated arcs, but still in one weld pool.

The electrode inter-distance is larger than for twin arc, typically between 8–20 mm (often in the range of 10–15 mm). For most of the welding systems, the electrode inter-distance is also dependent on the stick-out used, owing to the electrode angles in the welding gun. Tandem welding guns with neutral electrode angles do exist and for these systems, with sufficiently large electrode inter-distance, larger stick-outs and higher deposition rates are possible. Also, short arc welding can be used with these systems in different arc type combinations (Hedegård *et al.* 2004).

There are essentially two ways of avoiding arc disturbances, apart from the normal process optimisation and adaptation of welding parameters. One way is to increase the electrode inter-distance and by that reduce the interaction forces between the arcs. The other way is to use synchronised pulsed arc welding. The synchronisation is often, but not always, performed anti-clockwise. In this case, one arc will be in high current mode while the other is in base current mode (lower data, idle), and the arcs will shift to high mode (spray) in turns (see Fig. 8.10). The best synchronisation of the pulsed arcs is, however, dependent on the welding equipment, especially on the welding gun geometry and its synchronisation possibilities. It will need to be evaluated from case to case. Note: tandem arc MIG/MAG has a better chance of achieving stable welding than twin arc.

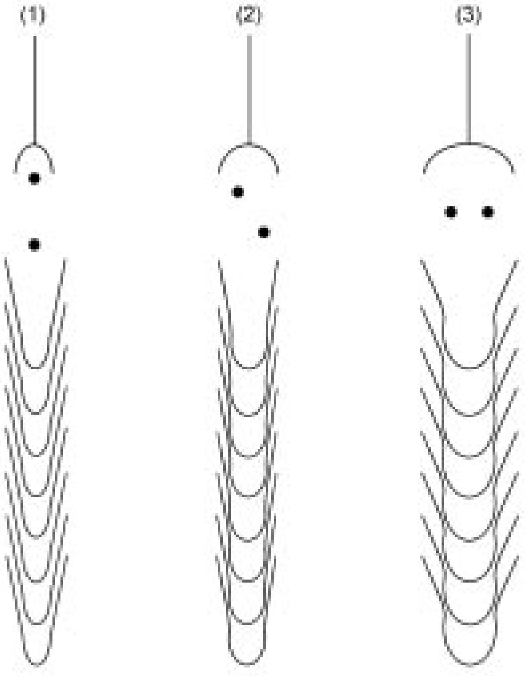


8.10 An illustration of pulsed arc welding with a tandem set-up (anti-clockwise pulsing). The arcs will not attract since the peak current times are not overlapping.

The orientation of the electrodes along the joint can be changed depending on the purpose (see Fig. 8.11). An orientation of one electrode after the other can result in high travel speed, while a slight twist of the welding gun can improve the gap bridgeability for the process. Parallel electrodes are used only for larger joints and slower welding speeds.

The application area for Tandem MIG/MAG welding is vast. Material thicknesses from approximately 2 mm to 20 mm can be welded with good results. Typical applications are:

- Wheels, beams, frames, cabins, rear axles for the vehicle industry.
- Girders, panels, exhaust systems for the shipbuilding industry.



8.11 An illustration of different electrode orientation. Case 1 is to maximise welding speed, case 2 is suitable for gap bridging, case 3 for high deposition welding and wider joints.

To make full use of the process, welding in the best position is recommended (this is valid both for twin and tandem arcs). By combining arc types and different filler materials, optimised weld geometry is found. With a combination of solid wire and core wire, interesting results are achieved: the solid wire in the leading position can create a deep penetration; the cored wire in the trailing position will ensure good sidewall fusion (Dilthey *et al.* 1998a).

Finally, a comment on the heat input calculation for double wire processes. It has been established that the heat input should be calculated as two separate parts (wire 1 and wire 2). These are then added together:

$$Q_{\text{tot}} = q_1 + q_2$$

The total heat input for the double wire welding methods compared to single wire methods is not necessarily larger. Naturally, it is dependent on how the process is set up, but often the heat input for tandem welding is equal to or only slightly higher than the single wire heat input. This is valid for single weld runs with limited weld size. For thicker plates, the heat input will be too high if the joint is filled up in one weld run. The demands on the joint in terms of Charpy-V toughness will decide the number of weld runs needed.

8.5 Hybrid welding: laser–MIG/MAG

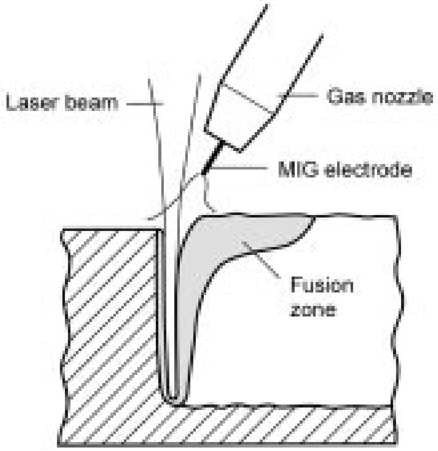
Laser–MIG/MAG welding is a beneficial combination of two welding processes where each process works in a complementary and stabilising manner with the other. The purpose is to gain both the laser and the MIG/MAG welding advantages. That is: high travel speed and deep penetration; high robustness and high gap bridgeability.

Laser hybrid processing was investigated initially in the 1970s, but without a real breakthrough. In the 1990s, attention was brought again to laser hybrid welding and especially to laser–MIG/MAG welding. It is a hybrid process since the two processes are set to act as one single process, as illustrated in Fig. 8.12.

The processes are positioned with typically 1–3 mm inter-distance on the workpiece. This is to enable a beneficial synergy between the processes.

Using laser welding only will result in a high travel speed and low heat input, but still with excellent penetration capacity due to the high energy density of the laser beam. A disadvantage is that laser welding requires high tolerances for the joint set-up due to the low gap bridgeability with the keyhole technology. Another negative aspect is when it is necessary to use filler material, the wire must then be added separately and it results in reduced laser power (melting the wire). Also, the high cooling rates for the laser process can in some cases result in solidification cracking or embrittlements.

MIG/MAG welding, on the other hand, is a more robust process in terms of positioning demands. It also has fairly high gap bridgeability and the filler material is added by molten metal transfer through the arc. MIG/MAG welding cannot, however, compete with laser welding in terms of travel speed and penetration capacity. The heat input can for some materials result in problems in the HAZ (heat affected zone).



8.12 An illustration of the laser–MIG/MAG welding process.

When these two processes are coupled together, the aim is to combine the positive aspects of each of the single processes and to avoid the disadvantages. For heavy section welding, a CO_2 laser is used due to its higher power level. For other applications, the Nd:YAG laser is a better choice since the light can be transported in fibres and thereby increases the flexibility for the welding (for better reachability).

The work principle for the laser–MIG/MAG process has been studied by many researchers. It can be described as follows: the laser beam initiates a keyhole in the joint, with metal vapour in the cavity that acts as a low ionisation-potential path for the electric arc. It has been suggested that the electric arc is stabilised by the effect of the laser, enabling the use of MIG/MAG welding at significantly increased travel speeds, which is one of the fundamental aims for the laser–MIG/MAG process.

There are many parameters to study, and set, for the laser–MIG/MAG process. Although laser hybrid welding technology has already come into use in parts of the industry, it is still in a developing phase. Therefore, only the basic elements of the process are discussed in this book. The interested reader is encouraged to study the process further in research articles as they appear.

The process can be set up in two ways: leading laser or trailing laser. Generally, leading laser appears to be more common and it results in a more laser-like welding and weld geometry. Using a trailing laser can, however, enable a more spread out weld geometry and give other benefits as well. Different set-ups and welding parameters will need to be evaluated for each case. The parameters to set are ‘all parameters for each process’ and mutual parameters such as the process head mounting angles (important) and inter-distance.

The power balance of the processes is also discussed, if the MIG/MAG process contributes with more than 60 per cent of the total welding power then the process is claimed to be ‘MIG/MAG dominated’. This will also be evident when examining the cross-section of the weldment. The power balance is calculated as

$$P_{\mathrm{Tot}} = P_{\mathrm{A}} + P_{\mathrm{L}}$$

where P_{A} is the amount of power from the arc and P_{L} is the contribution from the laser. Depending on how the power balance is set, the penetration profiles for the weldments can range from laser looking to MIG/MAG looking. Often, there is a mix so the top of the weldment cross-section reminds one of a MAG weld and the mid and root section has the typical laser appearance.

The first integrated welding heads have reached the market. These are suitable for mounting on welding robots. More equipment development is, however, expected.

The joint design can be optimised for laser hybrid welding. Apart from the possible increase in welding speed, this is another positive aspect for the hybrid process (with less machining required in many cases).

For thinner joints, the welding speed will be higher than for double wire MIG/MAG welding. For material thicknesses around 6 to 8 mm, the welding speeds are often more equal. The power of the laser system is, however, the key to the welding speed for the laser hybrid welding system (and to the cost of the equipment).

Apart from studying the welding speed, the mechanical properties of the weldments are of great interest for these processes. From different research trials, it is evident that although double wire MIG/MAG can achieve good mechanical properties, laser hybrid can be much better. This must be taken into account when comparing the different processes, their productivity and economy.

8.6 Process selection and cost comparison

A welding engineer of today has many welding processes to take into account. Process knowledge is always essential, but to be able to maintain production facilities in high salary countries, knowledge about the most productive and suitable welding methods is crucial.

The best process is not always the fastest or the least costly to purchase. For materials and consumables, the cheapest purchase may be too cheap and ruin the quality of the final product or be non-optimised when the total weld cost is considered. Often, a slightly more expensive material, filler material, or shielding gas is neglected owing to the higher purchase cost. But how is the total cost influenced? Often, a higher welding speed can be used with a more advanced shielding gas, and less scrap is produced when the steel plate is purchased with a better quality (less variance in the chemical composition, for instance, which will lead to a more consistant welding process).

A study of weld quality, reliability and flexibility *vs* the total weld cost for the product should be our guide in process selection, not solely the purchase costs. It is of utmost importance to make a weld cost calculation, even if it is simplified. Here, key numbers such as the cost per unit length of weldment or cost per hour in a welding station should be calculated. It is only then that knowledge about the most efficient welding method is accrued.

Even if double wire welding and laser hybrid welding are newer and highly productive methods, they will not necessarily be the better process in a cost *vs* quality and investment study. In some cases, single wire welding with high productivity is the better choice. However, in other cases the newer processes will win – and they should be used in more applications than they are today.

The laser hybrid process has so far been introduced in the car manufacturing industry where the part volumes are large. With reduced costs for future laser systems, the process will find more application areas. High productive MIG/MAG with single or double wire welding is used for a variety of components, such as beams, girders, axles, wheels, frames, containers, etc.

8.7 Future trends

The following ongoing and future trends can be identified:

- The double wire welding and laser hybrid welding processes are expected to continue to develop.
- More combined joining methods are expected since more advanced material combinations with different material types (aluminium to steel, for instance) will be used in products such as vehicles.
- A related process to MIG/MAG welding is arc brazing, or MIG brazing (discussed in Chapter 7). This process can be beneficial for joining of dissimilar metals, although a further development of suitable filler materials may be necessary. This area is expected to be further developed.
- The welding of (directly onto) coated steels has increased and is expected to continue. The challenge for the welder and welding engineer is to enable the welding process to also run with stability on thicker coatings. In some cases, special filler materials have been developed to improve process stability. This development is expected to continue.
- Pulsed arc welding with MIG/MAG (Chapter 6) has been developed and now double-pulse welding is possible. For single wire welding, this means that two pulse settings are used at the same time and the welding machine is alternating between the selected settings according to what is programmed. The application may be coated steels (to create a vibration of the weld pool and help to reduce the porosity in the weldment), or thin sheet joints. In some cases, it is also possible to alternate between a short arc and a pulsed arc (to reduce heat input), or only to use one controlled pulse but with a very low idle-mode (also to reduce heat input). These developments with advanced controlled pulses are expected to continue.
- New high strength filler materials will be developed to match the UHS steels.

8.8 Bibliography

Andersson J (2005) 'What is laser-hybrid welding', Conf. Laser Welding Days', 12–13 April 2005, Gothenburg, Sweden.

Anon (1993) *Facts about Rapid Arc Rapid Melt High-productivity MIG/MAG welding*, AGA AB, 1993.

Behler K (1995) 'Processtechnische Aspecte der Kombination des Laser-strahl-Lichtbogenschweisens', *Mechanik und Optik*, 33–48.

Bengtsson P (1993) 'Increasing productivity of metal-active-gas welding, it is possible', *Der Praktiker*, Vol. 45, No. 8, Aug, 428–430.

Church J G (1989) *Gas-Metall-Lichtbogenschweissverfahren*, AT Patentschrift R23985, 2154/89, DVR 0078016, 1989-09-14.

Church J G and Imaizumi H (1990) *Welding characteristics of a new welding process, T.I.M.E. Process*, Doc. XII-1199-90, IIW 1990.

Dilthey U, Borner A and Reisgen U (1996) 'Metal-arc active gas welding in the high power range with flux-cored wire electrodes', *Schweissen & Schneiden* (*Welding & Cutting*), No. 3, E47–E49, 200–208.

Dilthey U, Reisgen U and Bachem H (1998a), 'Increased productivity as a result of higher deposition rate and higher welding speed by using two-wire-GMAW process', Int. Conf: *Eurojoin 3*, 30 March–1 April 1998, 219–231.

Dilthey U, Reisgen U and Bachem H (1998b), *Two-wire processes for higher deposition rate and higher welding speed*, Doc. XII-1549-98, IIW 1998.

Dilthey U, Luder F and Wieschemann A (1999) 'Expanded Capabilities in the Welding of Aluminium Alloys with the Laser-MIG Hybrid Process'. *Aluminium*, 75(1-2), 64–75.

Dzelnitzki D (1999) 'Increasing the deposition volume or the welding speed? – Advantages of heavy-duty MAG welding', *Welding and Cutting*, No. 9, E197–E204.

Hackl H (1998) 'Faster with two wire electrodes – metal inert gas welding of aluminium materials', Int. Conf: *Exploiting advances in arc welding technology*, Cambridge, 30–31 March 1998, 51–54.

Halmoy E (1979) *Pulsating welding arcs*, SINTEF Report STF16A79021, 1979.

Halmoy E *et al.* (1991) *The T.I.M.E. welding method compared with GMAW*, Doc. XII-1248-91, IIW 1991.

Hedegård J and Lundin M (2001) 'Tandem wire MAG welding, a process study', SIMR Research Report, No. IM-2001-507, 2001.

Hedegård J, Weman K and Lundin M (1997) 'High productive MAG-welding – An evaluation of Rapid Arc and Rapid Melt', NESCO 1, Nordic Conf. *Welded High-Strength Steel Structures*, Stockholm, Sweden, 8–9 October 1997, 3–17.

Hedegård J, Andersson J, Tolf E, Weman K and Lundin M (2004) *Enhanced prospects for Tandem MIG/MAG welding*, Doc. XII-1808-04, IIW 2004.

Herrich J and Rippl P (2002) 'Hybrid Laser Beam and MIG/MAG Welding', *Der Praktiker*, 54(5), 178–181.

Krivtsun I V (2001) 'Peculiarities of Penetration of Metal in Laser-arc Welding Using YAG Laser'. *Paton Welding Journal*, 12, 29–32.

Lesnewich A (1958) 'Control of melting rate and metal transfer in gas-shielded metal arc welding', Parts 1 and 2, *Welding Journal*, Aug 1958, 343–353, Sept 1958, 418–425.

Lesnewich A (1959) Electric arc welding, US Patent 2.916.601, 8 December 1951.

Lundin M, Hedegård J and Weman K (1997a), 'High productive MAG-welding – a comparison of methods', NESCO 1, Nordic Conf. *Welded High-Strength Steel Structures*, Stockholm, Sweden, 8–9 October 1997, 19–31.

Lundin M, Hedegård J and Weman K (1997b), 'An evaluation of the Rapid Arc process', Int. Conf. *JOM-8*, Helsingor, Denmark, 12–14 May 1997, 94–99.

Matsuda J and Utsumi A (1988) 'TIG or MIG Arc Augmented Laser Welding of Thick Mild Steel Plate'. *Joining and Materials*, 1, 31–34.

Mitchie K, Blackman S and Ogunbiyi T (1999) 'Twin-wire GMAW: process characteristics and applications', *Welding Journal*, May, 31–34.

Morehead T (2003) 'Automatic Multiwire GMAW Multiplies Productivity', *Welding Journal*, June, 40–43.

Nilsson K (2003) 'CO2-Laser/Pulsed MIG Hybrid Welding of High Strength Steel', *NOLAMP 9*, Trondheim, Norway.

Norrish J (2003) *A review of metal transfer classification in arc welding*, Doc. XII-1769-03, IIW 2003.

Olsson R, Bengtsson P and Stares A (1995) *High-speed welding gives a competitive edge*, Doc. XII-1418-95, IIW 1995.

Pace D P, Kenney K L and Galiher D L (2002) ‘Laser Assisted Arc Welding of Ultra High Strength Steels’, *6th Int. Trends in Welding Research Conf. Proc.*, Pine Mountain, GA, USA.

Savu D (1999) ‘Electromagnetic interactions in two-wires MIG/MAG welding’, IIW Doc. XII-212-944-99: Int Conf: *ISIM*, Timisoara, 1999.

Staufer H, Rührnösl M and Miessbacher G (2002) *LaserHybrid Welding and LaserBrazing: State of the Art in Technology and Practice by the Examples of the Audi A8 and VW-Phaeton*. Fronius International GmbH, Wels, Austria, p. 10.

Staufer H, Miessbacher G and Rührnösl M (2003) ‘Hybrid Welding for the Automotive Industry’, *Industrial Laser Solutions*, Feb.

Steen W M (1980) ‘Arc Augmented Laser Processing of Materials’. *J. Appl. Phys.*, 11, 5636–5641.

Trube S (1997) ‘High performance MAG welding with the LINFAST concept’, *Sonder drück* 36/97, Linde AG (bilingual, in German and English).

Trube S and Ladi Z (1995) ‘Influence of the shielding gas/welding wire combination on the stability of metal transfer in MAG high power welding’, *Welding and Cutting*, No. 12, E224–E227.

Weldingh J and Kristensen J K (2003) ‘Hybrid YAG-Laser/MAG Welding, Quality and Stability’, *NOLAMP 9*, Trondheim, Norway.

Weman K and Hedegård J (1998) ‘High-productivity welding of thin sheet steel – an overview of methods’, *Svetsaren*, No. 3, 36–39.

Weman K and Pekkari B (2004) Energy efficiency in welding processes, Doc SC-ENV 47-04, IIW 2004.

West D S, Neuberger J, Lahnsteiner R and Overton A (1991) ‘Revolutionary improvements in automated robot welding’, TWI Conf. *Automated welding systems in manufacturing*, Gateshead, North East UK, 17–19 November 1991. TWI paper 35.

9

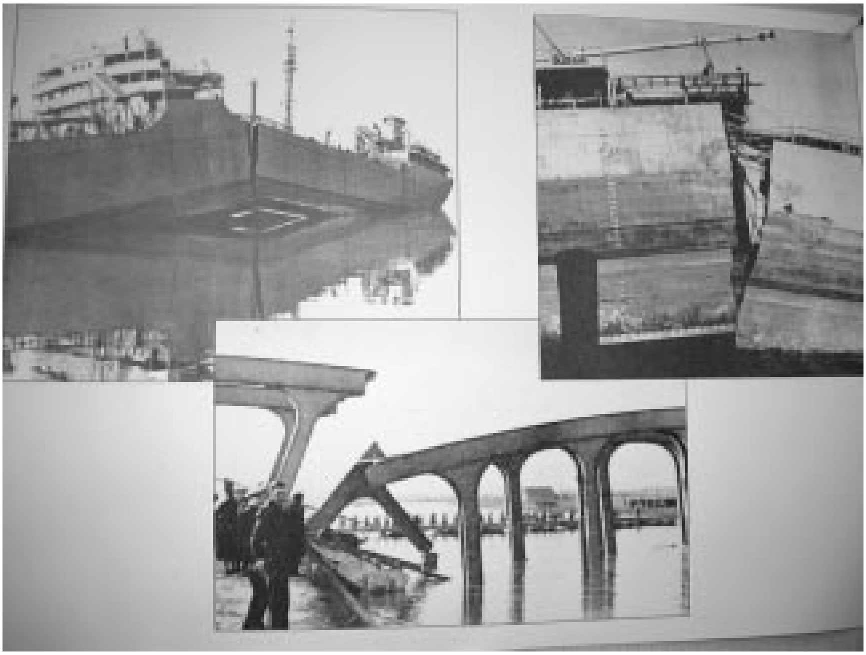
Assessing weld quality in MIG welding

P NERMAN, Corrosion & Metals Research Institute, Sweden

9.1 Introduction

Weld quality is a wide term that can be defined in many ways depending on the user and the application. In many everyday applications such as cooking ware, leisure equipment, etc., the demands of the ingoing welds are often moderate and limited just to visual appearance. At the other end of the range there are aerospace and nuclear applications where the demands of the ingoing welds can be very stringent. However, independent of the application, a weld can more or less always be considered to be the weak link in a construction. This fact has been well known since the earliest days of fusion welding (~1900). In spite of that, the weld quality issues did not become really important until the 1930s when new highly productive fusion welding methods (submerged arc welding (SAW) etc.) were introduced in the manufacturing industry. Between the 1930s and 1950s several major accidents occurred in fusion welded constructions due to lack of understanding of the weld quality issues. Two well known examples are the Hasselt bridge in Belgium and the ship *Schenectady* (see Fig. 9.1). These accidents were caused mainly by a combination of weld defects and steels with a low impact strength at low temperatures.

With experience of these and other severe accidents a lot of national and international standardisation work started up in the late 1940s with the specific purpose of improving the understanding of weld quality issues. The major player in the international standardisation work was (and still is) the International Institute of Welding (IIW) which was founded in 1947. The main tasks for the standardisation work were to standardise both the weld quality in itself and the filler and base materials used for welding. This work, which is still ongoing, has resulted in many different standards (national and international) both for weld quality and for the ingoing materials in a weld. The trend today is to use more of the international standards instead of the national standards. The international standards are denominated 'ISO xxx' while the national standards can have many denominations depending on their country of origin such as 'ASME xx' (USA), 'BS xx' (UK), 'DIN xx' (Germany), 'SS xx' (Sweden) and many more.



9.1 The 'cleavage' of *Schenectady* (top left and right) and the Hasselt bridge (bottom).[4]

The weld material standards are not discussed further in this chapter but a few more general words are worth mentioning about the definitions of 'weld quality'. Generally the imperfections in a weld can be denominated as 'flaws' or 'defects' depending on their influence on the structural integrity of a construction. A weld 'flaw' is a type of imperfection that more or less only influences the appearance of the weld. A weld 'defect', on the other hand, is a type of imperfection that more or less always has a major influence on the structural integrity of a construction. Examples of weld flaws are spatter, discoloration and surface slag remnants while cracks, lack of fusion and root defects represent common types of weld defects. In some cases, such as for porosity, the weld imperfection can be regarded as a 'flaw' or a 'defect' depending on its size and position in the weld. For this reason most modern weld quality standards have adopted the denomination 'weld discontinuities' which covers all types of weld imperfections.

9.2 Weld discontinuities

Metal inert/active gas welding (MIG/MAG) is a relatively new fusion welding process that was introduced on the market in the mid-1950s. It has become the single most used fusion welding process in the manufacturing industry today.

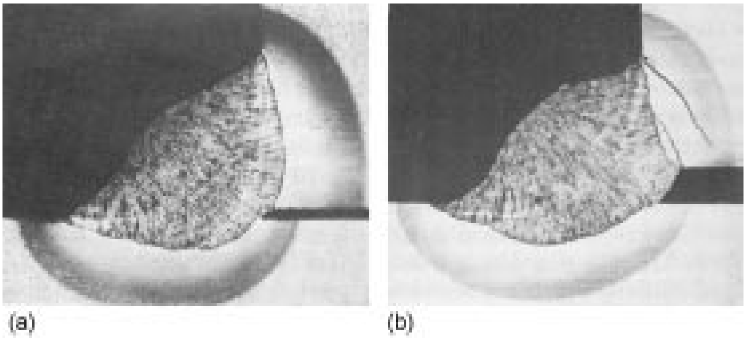
The reasons for this are several but one of the most important is the relatively high productivity compared to manual metal arc welding (MMA) and other manual processes (tungsten inert gas welding (TIG), oxy-acetylene, etc.). The process is also very flexible and easy to implement in mechanised welding stations (robot cells, etc.). When the process was new it was also considered to be very easy to learn and use compared to other fusion welding processes ('any fool can do it'). Very soon, however, it turned out that some types of weld discontinuities seemed to be more common with the MIG/MAG process compared to other fusion welding processes. In the following text some of the most important weld discontinuities in MIG/MAG are described. Acceptance criteria for each weld discontinuity, according to one of the most well known weld quality standards, ISO 5817 ed. 1, are also given.[2] In this standard three different weld quality levels (B, C and D) are defined where B is the most stringent level. Level B is often applied when the demands on the finished weld are high. Common examples here are pressure vessels and aerospace applications.

9.2.1 Root defects

This type of weld discontinuity is more common with MMA and MIG/MAG with cored electrodes than with other welding processes. In ISO 5817 ed. 1,[2] root defects are regarded as a serious weld discontinuity which is not acceptable at all at level B (most stringent) and only to a very small extent at the less stringent levels, C and D. A root defect can also induce other serious weld discontinuities, such as solidification cracks, as is shown in Fig. 9.2.

Root defects in MIG/MAG welds can be caused by several reasons of which the most common are mentioned below:

- Too small a heat input (too low a weld current/too high a travel speed).



9.2 An increase in size of root gap raises the stress imposed on the weld and causes cracking even when hydrogen levels and welding conditions are held constant.

- Unfavourable torch position relative to the root area in the joint (torch positioned on one of the side walls of the joint instead of in the middle of the bottom area of the joint).
- Too narrow a joint configuration (too small a gap width/too small a joint angle).
- Plate edge misalignment (see Figs 9.2 and 9.4) or varying gap width.

Counteractions against this type of weld discontinuity are proposed in the following statements:

- Increase the heat input (increase the weld current and/or decrease the travel speed).
- Use a favourable torch position (in the middle of the bottom area of the joint).
- Make the joint wider (increase the gap width and/or increase the joint angle). It must be noted here, however, that too big a gap width can increase the risk of solidification cracks (see Section 9.2.3). Gap widths in the range of 1–3 mm and V-joint angles in the range of 50–60° are often recommended by the plate/filler material manufacturer.
- Minimise the plate edge misalignment and ensure that the gap width is constant along the weld. This is especially important in mechanised welding where the welding speeds usually are much higher and the adjustment of welding process parameters is less intuitive compared to manual welding. In other words, a skilled welder can usually compensate much more easily than a welding machine for a varying gap width and plate edge misalignment.

This type of weld discontinuity is normally not dependent on the material type even if some nitrogen alloyed stainless steels can require a wider joint than usual (V-joint angle of 70° instead of 50–60°). The occurrence of root defects is, however, to some extent, dependent on the operator (unfavourable choice of process parameters and/or torch position).

9.2.2 Lack of fusion

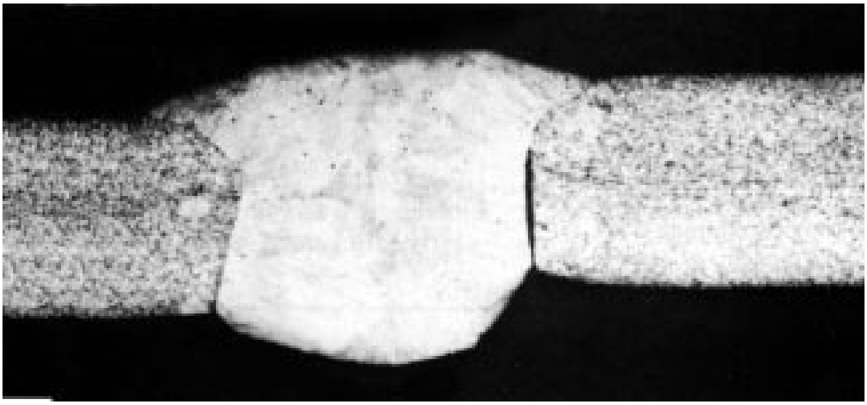
Lack of fusion (LOF) is a serious type of weld discontinuity that can occur under certain conditions with nearly all types of fusion welding methods. In MIG/MAG, LOF has, however, been reported to occur more often compared with other common welding methods such as MMA and TIG welding.

During the last decade, however, it seems that the LOF problem in MIG/MAG welding has diminished. This has been reported to be due to new types of power sources (synergic pulsing capabilities) and filler materials (metal cored wires). It must also be stated that the basic understanding of the MIG/MAG welding process is much deeper now than for one or two decades ago. The method has, in any case, got a bad reputation in the field especially for applications with stringent quality requirements such as pressure vessels mainly due to this weld discontinuity. Several demanding customers and third party inspection bodies still demand extra examinations (bend tests, etc.) when using MIG/MAG in a welding procedure qualification instead of other common welding methods (TIG, MMA, etc.). This is regarded as frustrating in the manufacturing industry since MIG/MAG is a very flexible and highly productive welding method. Hopefully, the improvements in process and filler material technology will help to change this bad reputation with time.

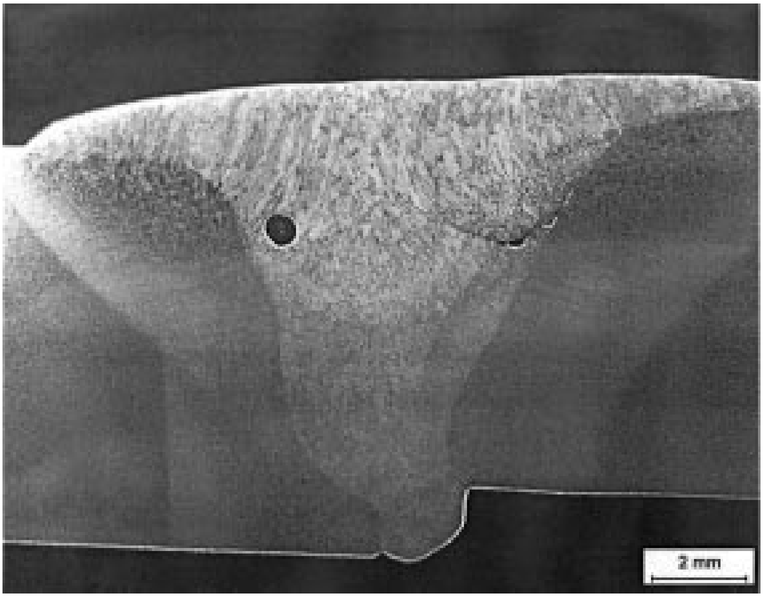
In ISO 5817 ed. 1, LOF is regarded as a serious weld discontinuity which is not accepted at all at level B or C and only to a very small extent in the least stringent level D. The typical appearance of LOF in two different types of MIG/MAG welds is shown in Figs 9.3 and 9.4. In these pictures the nature of LOF as a planar or semi-planar weld discontinuity is clearly shown. This fact often makes this type of weld discontinuity harder to detect with NDT compared to other types of weld discontinuities, see Section 9.3 for further comments.

LOF in MIG/MAG welds can be caused by several reasons of which the most common are mentioned below:

- Too small a heat input (too low a weld current/too high a travel speed).
- The arc type seems to have an important influence on the occurrence of LOF especially for thicker plate (> 8 mm), a lot more LOF has been reported when using short arc instead of spray arc in 8 mm plate.[3]
- Too much molten material in the joint and/or too low a travel speed which can cause the molten material to advance before the weld arc and cause LOF. This phenomenon is most likely to occur in unfavourable welding positions such as vertical/inclining down (see Fig. 9.5).
- Unfavourable torch position in relation to the welding position, this is also most important in unfavourable welding positions such as vertical/inclining down. An unfavourable torch position in, for example, the inclining down



9.3 Typical LOF in a single pass MIG/MAG weld (black vertical line to the right of the weld).[1]

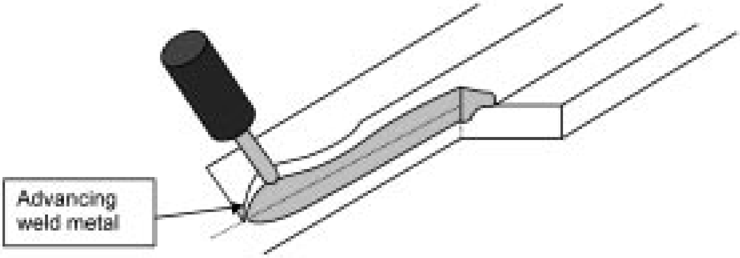


9.4 Typical LOF in a two pass MIG/MAG weld (black vertical 'bow' to the right in the weld), please also notice the big pore to the left in the figure and the severe plate edge misalignment (bottom of the figure).[3]

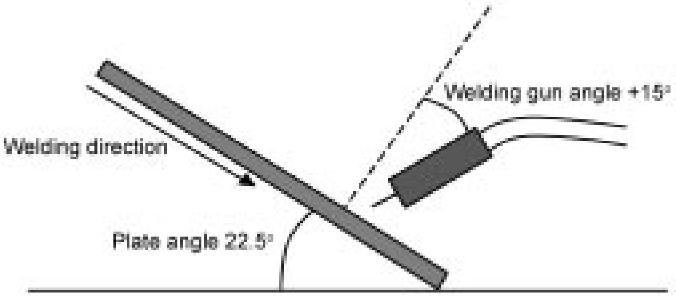
welding position will make it easier for the molten weld metal to advance before the weld arc and cause LOF.

- Too narrow a joint configuration (too small a gap width/too small a joint angle).
- Positioning the torch against the thinner plate when welding in joints with a big difference in plate thickness.

Counteractions against this type of weld discontinuity are proposed in the following statements:



9.5 Advancing weld metal in inclined downhill/vertical down MIG/MAG welding.[6]



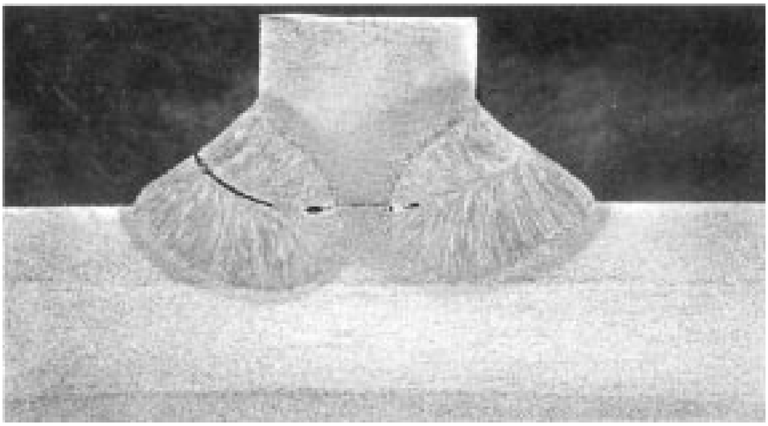
9.6 Favourable torch position (backhand) in downhill inclined MIG/MAG welding.[6]

- Use a higher heat input (increase the weld current and/or decrease the travel speed).
- Balance the wire feed speed in relation to the travel speed.
- If possible, avoid short arc when MIG/MAG welding in thicker plates (> 8 mm).
- Use a favourable torch position in relation to the welding position. A backhand torch position (see Fig. 9.6), is usually most favourable especially in vertical/ inclining down welding positions. This can be understood by the fact that the arc pressure will help to 'push up' the molten material in the joint and therefore prevent the molten material from advancing before the weld arc.
- Make the joint wider (increase the gap width and/or increase the joint angle). It must be noted here, however, that too big a gap width can increase the risk of solidification cracks, see Section 9.2.3. Even here, gap widths in the range of 1–3 mm and V-joint angles in range of 50–60º are often recommended by the plate/filler material manufacturer.
- Position the torch against the thicker plate when welding in joints with a big difference in plate thickness.

This type of weld discontinuity is normally not dependent on the material. The occurrence of LOF is, however, highly dependent on the operator, especially in manual MIG/MAG. Even if this type of weld discontinuity is still regarded as frightening, it could in most cases be avoided if proper measures are taken and a qualified welding procedure is used.

9.2.3 Solidification cracks

This type of discontinuity can occur with all fusion welding methods. In ISO 5817 ed. 1 all types of cracks except microcracks (height × length < 1 mm^2) are regarded as serious weld discontinuities which not are accepted at all in any of the quality levels B, C or D. Solidification cracks are often surface breaking (see Fig. 9.7), but could also be non-surface breaking (see Fig. 9.8).



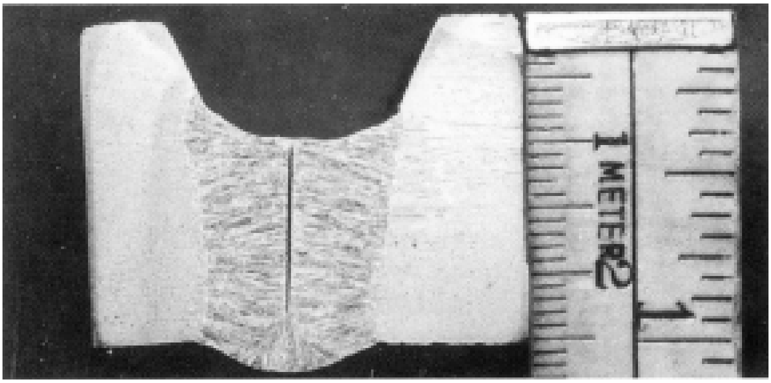
9.7 Typical surface breaking solidification crack in a T-joint.[1]

Solidification cracks in welds can be caused by several reasons of which the most common are mentioned below:

- The chemical analysis of the base material and/or filler material. High levels of impurities such as sulphur and phosphorus are in general unfavourable. A high carbon and niobium content will also promote this type of crack in carbon steels. Manganese and silicon can, on the other hand, help to decrease the risk for this type of crack in carbon steels. The following cracking index for assessment of the probability of solidification cracking in submerged arc welds in carbon-manganese steel has been developed by Bailey and Jones:[5]

  $$U_{CS} = 230C + 190S + 75P + 45Nb - 12.3Si - 5.4Mn - 1$$

  The amount of each element, C etc., is given in percentage mass. Solidification cracking of fillet welds is likely if $U_{CS} > 25$. Weld pass/joint



9.8 Typical non-surface breaking solidification crack in a V-joint.[1]

shape and other factors mentioned further in this work may alter the risk for solidification cracks to some degree. The solidification mode also plays an important role here. A ferritic-austenitic solidification is known to give the best resistance to solidification cracking while pure austenitic solidification will promote solidification cracking. Pure austenitic solidification occurs in certain high alloyed stainless steels and nickel base alloys.

- Unfavourable width/depth ratio (<1) of the weld pass and/or joint.
- Too high a degree of restraint of the joint. This can be caused by too high a heat input, severe forming operations, thick plates and heavy clamping.
- Too big a gap width.

Counteractions against this type of weld discontinuity are proposed in the following statements:

- Choose base and filler material with documented resistance to solidification cracking.
- If possible choose welding data and/or joint configuration in such a way that a width/depth ratio > 1 of the weld pass and/or joint is obtained.
- Minimise the degree of restraint of the joint by, for example, not using too high a heat input and too heavy clamping.
- Only use a gap width big enough to avoid root defects and lack of fusion (see Sections 9.2.1–2). The plate/filler material manufacturer usually recommends a gap width of 1–3 mm.

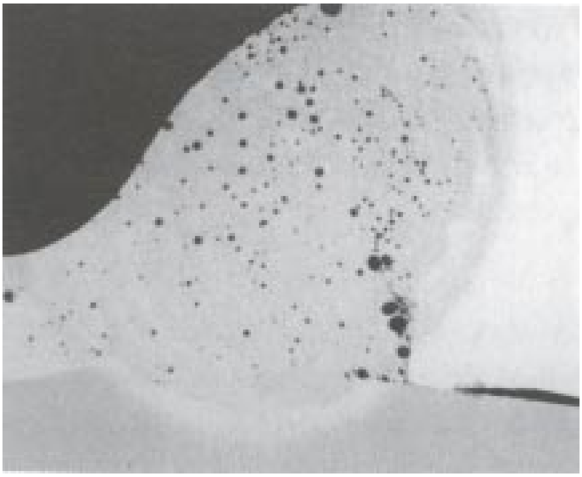
This type of weld discontinuity is highly dependent on the material type. Certain nickel base alloys, aluminium alloys and high alloyed stainless steels are sensitive for this cracking mechanism. Other materials can also be sensitive if they contain high levels of impurities such as sulphur and phosphorous. The occurrence of solidification cracks is, however, only to a small extent dependent on the operator (heat input, clamping, etc.).

9.2.4 Porosity

This type of discontinuity is more common with MIG/MAG and SAW compared to other welding processes. Porosity is, however, not regarded as a serious weld discontinuity unless the amount of and/or size of the pores exceed high levels. In ISO 5817 ed. 1, local clusters of spherical pores are accepted to quite a high degree in all three quality levels B, C and D (4% (level B) –16% (level D) of the projected weld area). Elongated pores are only accepted in the least stringent level, D. Pores could both be surface breaking or non-surface breaking (see Fig. 9.9).

Porosity in MIG/MAG welds can be caused by several reasons of which the most common are mentioned below:

- Dirt (oil, grease, etc.), rust and/or humidity on the material to be welded.
- Welding of Zn-coated and/or painted material especially in lap joints.



9.9 Porosity in a MIG/MAG weld in aluminium.[1]

- Insufficient shielding gas protection of the weld area caused by turbulent/disturbed shielding gas flow, too low a shielding gas flow or impurities in the shielding gas itself. Turbulent/disturbed shielding gas flow can be caused by wind, too high a shielding gas flow or adhering spatter in the shielding gas nozzle. Impurities in the shielding gas itself are usually caused by leakage of air and/or humidity into the shielding gas system. This in turn is usually caused by defective/unsuitable hoses and/or couplings and more seldom by contaminated gas in the bottle.

Counteractions against this type of weld discontinuity are proposed in the following statements:

- Clean the plates of dirt, rust, humidity and/or paint prior to welding.
- Use only dedicated filler materials and welding procedures when welding Zn-coated material especially in lap joints.
- Do not weld in wind.
- Use a properly adjusted shielding gas flow for each welding situation (not too low or high), see the recommendations given by the welding material and/or gas supplier.
- Check hoses and couplings regularly for leakage. Be sure that hoses and couplings are of a suitable type. Even here it is a good idea to look for recommendations given by the welding material and/or gas supplier.
- Keep the shielding gas nozzle clean from adhering spatter.

This type of weld discontinuity is to some extent dependent on the material type. Porosity often occurs in aluminium alloys, Zn-coated materials and certain high alloyed stainless steels. Independent of material type, porosity also often occurs using MIG/MAG at high data with flux cored filler wires. The occurrence of porosity is, however, only to a limited extent dependent on the operator.

9.2.5 Spatter

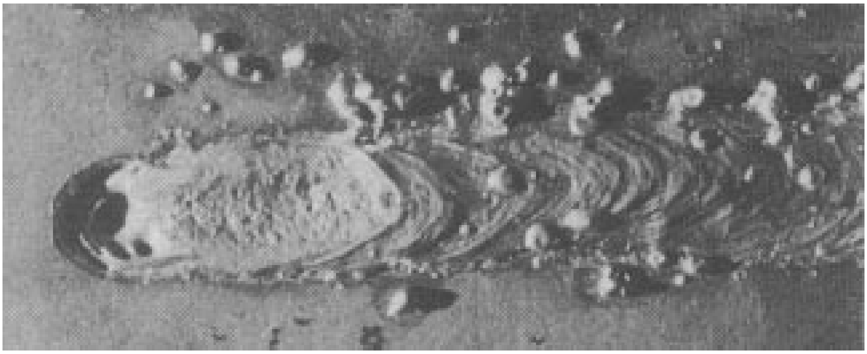
This type of discontinuity is more common with MIG/MAG and MMA compared to other welding processes. Like porosity, spatter is, however, not regarded as a serious weld discontinuity unless the amount of and/or size of the spatter exceeds high levels. In ISO 5817 ed. 1, spatter is accepted in all three quality levels B, C and D. Whether spatter can be accepted or not is dependent on the application in each case. Spatter is a typical surface discontinuity (see Fig. 9.10).

Spatter on MIG/MAG welds can be caused by several reasons of which the most common are mentioned below:

- Unsuitable choice of shielding gas for the chosen combination of base/filler material and arc type. High CO_2 content in the shielding gas will, in combination with high welding current, give coarser adhering spatter.
- Unsuitable choice of welding process parameters/conditions which can give unstable and/or too long an arc which in turn will give a lot of spatter.
- Unsuitable filler material.
- Contaminated filler material (dirty, greasy, etc.).

Counteractions against this type of weld discontinuity are proposed in the following statements:

- Choose a suitable shielding gas and filler material. Use the recommendations given by the supplier of filler material/gas.
- Use suitable welding process parameters/conditions.
- Use only clean filler material.
- Changing from a stationary arc (short arc or spray arc) to a pulsed arc can in some cases be very helpful in order to reduce spatter.

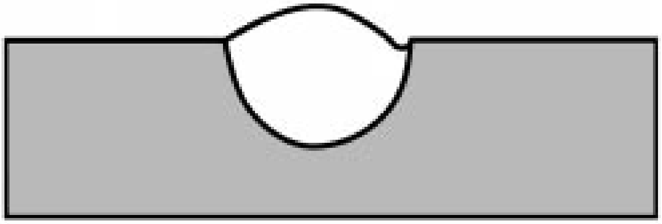


9.10 Spatter on a MMA weld.[1]

This type of weld discontinuity is dependent both on the material/gas type and the operator (process parameters).

9.2.6 Undercut

This type of discontinuity occurs independent of the welding process. Like porosity and spatter, undercut is, however, not regarded as a serious weld discontinuity. In ISO 5817 ed. 1, undercut is accepted in all three quality levels B, C and D to quite high levels (depth: 0.5 mm (level B) – 1.5 mm (level C)) as long as the transition between the weld and the base material is smooth. Whether undercut can be accepted or not is dependent on the application in each case. Undercut is a typical surface discontinuity (see Fig. 9.11).



9.11 Typical appearance of undercut in a MIG/MAG weld (to the upper right of the weld).

Undercut in MIG/MAG welds can be caused by several reasons of which the most common are mentioned below:

- Undercut is often caused by too high an arc voltage in relation to the weld current.
- High travel speed will often promote undercut.
- Unfavourable position of the welding electrode in the joint.

Counteractions against this type of weld discontinuity are proposed in the following statements:

- Balance the arc voltage in relation to the weld current.
- Decrease the travel speed to a level where undercut does not occur.
- Use a favourable position of the welding electrode in the joint (in the middle).

This type of weld discontinuity is highly dependent on the operator (process parameters) and only to a lesser degree on the material type.

9.3 Non-destructive testing (NDT) methods and their applicability on different types of weld discontinuities

In order to verify the quality of a finished weld both destructive methods (impact testing, tensile testing, metallograhpic examination, etc.) and non-destructive testing methods (ultrasonics, X-ray, etc.) can be used. For economic and practical reasons the use of destructive methods is, however, limited mainly to welding procedure and/or welding operator qualifications. In order to verify the quality of a weld in a construction or a product it is most practical and economical to use NDT-methods. Several NDT-methods have been developed but only a few are used regularly in the manufacturing industry and by third party inspection bodies. These methods are:

- Ultrasonic testing (UT).
- X-ray (RT).
- Visual inspection (VT).
- Dye penetrant testing (DP).
- Magnetic particle testing (MT).

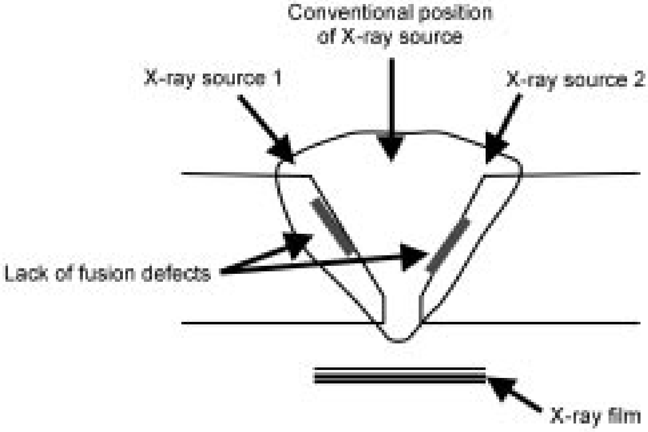
UT and RT can be used for detecting both surface breaking and non-surface breaking weld discontinuities while VT, DP and MT can only be used for detecting surface breaking weld discontinuities. In the following text the applicability of UT, RT, VT, DP and MT are discussed for each of the weld discontinuities mentioned in Section 9.2. For MT it must be noted that this NDT method is only applicable for ferro-magnetic materials.

Root defects can often be detected by VT, MT or DP before welding of an eventual back pass. Root defects in T-joints can only be detected by either UT or RT, depending on accessibility. Independent of weld type and NDT method root defects are usually easy to detect because they are often quite open.

Surface breaking lack of fusion (LOF) can be detected by VT, DP, MT, UT or RT. Non-surface breaking LOF can only be detected by RT or UT. Since LOF is a planar or semi-planar weld discontinuity which is usually quite closed it could sometimes be hard to detect with VT or RT. If LOF is suspected to occur in a certain type of weld it could be a good idea to use a special NDT-procedure which is optimised for its purpose to find LOF in the specific type of weld to be tested. An example of a LOF-optimised RT-procedure for use in V-joints is shown in Fig. 9.12.

In this optimised procedure two X-ray sources are used instead of the usual one. These two X-ray sources are also inclined along the sidewalls of the joint, which improves the possibility of finding LOF (both surface and non-surface breaking). UT is usually the best NDT method for finding LOF but has limitations in stainless steels especially within the weld deposit.

Surface breaking solidification cracks can be detected by VT, DP, MT, UT or



9.12 Optimised X-ray procedure used to find LOF in V-joints.[3]

RT. Non-surface breaking solidification cracks can only be detected by RT or UT. Solidification cracks are often quite open which usually makes them easy to detect independent of NDT method.

Surface breaking pores can be detected by VT, DP, MT, UT or RT. Non-surface breaking pores can only be detected by RT or UT. Pores can, however, often give a misleading signal response with UT.

Undercut and spatter are normally best detected by VT but can also be detected by RT or UT (undercut only).

Finally, it must be noted that it is seldom sufficient to use only one NDT method in order to verify the quality of a finished weld. Two or even more NDT methods are often used in the manufacturing industry and by third party inspection bodies in the weld quality verification process.

9.4 References

1. Nerman, P., *Vägledning till godkända svetsförband*, SIMR-report no. IM-2000-007.
2. *Arc-welded joints in steel – Guidance on quality levels for imperfections*, SS-ISO 5817 ed. 1, 1993-02-26.
3. Nerman, P., *Aspects on problems with lack of fusion in MIG/MAG-welding*, IIW-XI-767-02.
4. Hannerz, N.E., *Svetsningens materialteknologi*, The Institution for Materials Process Technology KTH, Stockholm 1999.
5. Lancaster, J.F., *Metallurgy of Welding*, 6th edn, 1999.
6. *Influence of the weld metal flowability on the welding result*, diploma work by Catarina Ericsson, SIMR-report no. IM-2001-040.

10

Occupational health and safety in MIG welding

K WEMAN, Wemab AB, Sweden

This chapter contains both pictures and text that, with permission from ESAB, is copied from their publication *Welding and cutting – risks and measures*, see Section 10.12.

10.1 Introduction

Welders are members of an occupational group which is exposed to a number of different environmental problems. This chapter deals with the different factors in the welders' working environment, as well as suitable measures that can be implemented to improve this environment and reduce the health risks. A good welding environment is increasingly important, and access to qualified welders is essential to obtain good quality and productivity.

MIG welding, like all other forms of welding, exposes the welder to health hazards unless suitable precautions are taken. The main health hazards associated with MIG welding are fumes and gases, together with ultraviolet radiation from the arc. A wide range of equipment is nowadays available for protection: examples are welding guns with integrated fume extraction, welding glass that the welder can see through while setting up the job, but which darkens instantly when the arc is struck, and shielding gases that substantially reduce the amount of ozone formed.

The working environment is one of the factors that have an effect on the choice of occupation.

10.2 Electrical hazards

Arc welding is unavoidably associated with the risk of contact with live parts. It is therefore important to be acquainted with the risks and to know how to avoid them. Human beings are extremely sensitive to current that passes through their bodies: serious physical injury can be caused by currents of just 20 or 30 mA.

Physical injuries, such as falling from scaffolding or a ladder, can result indirectly from very low currents as a result of a sudden and involuntary reaction to an electric shock. The choice of the type of current (alternating or direct) during arc welding is important, as the risks associated with alternating current (AC) are as much as four times greater than those associated with direct current (DC).

The effects that result from current passing through the human body depend on:

- the level and duration of the current,
- the current path through the body,
- the frequency of the current.

The danger of ventricular fibrillation in the heart depends on the path of the current through the body, i.e. the level and time of current passing through the heart. As mentioned above, the risks associated with alternating current are higher than for direct current. We are most sensitive in the frequency range of 15–100 Hz.

The level of the current depends on the open circuit voltage of the power source and also on the resistance of the body. The resistance varies, depending on the size of the contact surface of the live parts, the presence of moisture and the quality of protective clothes and gloves the welder is using.

10.2.1 Increased hazard of electric shock

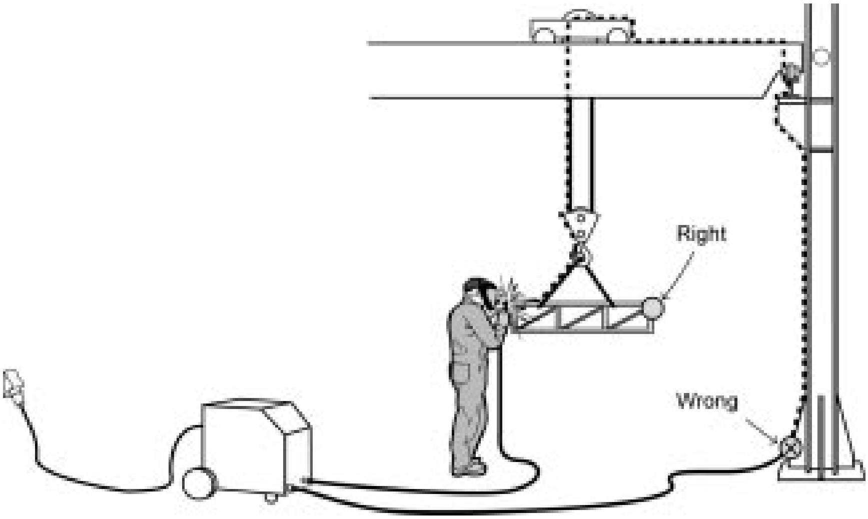
Direct current is an advantage when welding in a confined space where the risks are greater (such as moist, hot or confined spaces with conductive parts or walls). The risk that the operator will get an electric shock is increased when he or she works in such spaces.

10.2.2 Safety in welding operation

Damage to material or equipment may occur if the return cable is connected inappropriately. It should be connected as close to the welding point as possible. The size of welding cable needs to be chosen to suit the highest welding current used, and the cable connection must be fixed in such a way as to ensure that it cannot come loose.

It is not only weld spatter that can cause fires: heating caused by the welding current also presents a risk. If, for example, the return conductor is not properly connected, the return current may take a different path, with resulting overheating and ignition at unexpected positions.

If the welding current returns via the wrong paths, it can also cause damage to mains cables and protective earth connections, as they are not of a size to carry such currents. Damage can also occur if the workpiece is earthed and there is a fault in the welding current circuit.



10.1 To avoid damage to material or equipment the return cable should be connected close to the welding point.

Stray currents through crane cables or lifting hooks can cause partial or complete annealing (see Fig. 10.1). In the same way, damage can be caused to the bearings of rotating machines if sufficiently high currents pass through them.

10.2.3 Welding equipment

Routine inspection of equipment

If the internal cooling surfaces of a power source are clogged up with dust and dirt, the temperature increases. It is important from a safety point of view to avoid overheating. A breakdown of the insulation between the primary and secondary windings in the transformer may permit the mains voltage to reach the welding circuit. The insulation resistance may also deteriorate from conducting dust caused by grinding. As the secondary circuit is not necessarily connected to earth, this would be hazardous to the welder. It is therefore recommended that equipment should be routinely inspected and cleaned internally.

Protection provided by the enclosure

Power sources should have protection for solid foreign objects and water penetration provided by the enclosure (IEC 60529). The degree of protection is indicated by the IP code (International Protection) on the rating plate. Power sources for outdoor use must have a minimum degree of protection of IP23.

Insulation requirements

A welding circuit is not protectively earthed, and so it is important that the power source is insulated in accordance with EN 60974-1 in order to ensure that the mains voltage cannot reach the secondary circuits.

Transformer winding insulation is exposed to high temperatures, so the material must be of a suitable insulation class to withstand the temperature. A rise of 10 °C reduces the life of the material by half. Therefore it is particularly important to keep the interior of the power source clean in order to maintain adequate cooling performance.

Despite all these measures, the welder should still take care: the use of gloves, together with undamaged dry clothing, is recommended.

Open-circuit voltage

It is important from the point of view of electrical safety that the open-circuit voltage of the power unit is not too high. This is particularly important when using AC for welding, where a high open-circuit voltage is often required in order to ensure a stable arc. At the same time, health and safety requirements are particularly strict in connection with the use of AC. The standard EN 60974-1 permits a maximum of 80 V AC, as compared with 113 V DC. Open-circuit AC voltage may not exceed 48 V in wet areas or confined spaces, which are regarded as presenting a higher electrical safety risk. Equipment suitable for welding with the increased hazard of electric shock may be marked with the S symbol on the rating plate.

Rating data

The power unit rating plate shows all the relevant information concerning the rating of the unit. The most important details are those relating to rated currents, rated voltage and intermittence. Other important details are efficiency and power factor, open-circuit voltage, insulation class, etc. (see Fig. 10.2).

IEC/EN 60974-1 specifies how power units must be marked and tested.

10.3 Electromagnetic fields

Measurements have shown that the magnetic flux density close to welding cables may exceed the limit values at high current arc welding. A new EU directive brings the problem into focus, as it makes the employer responsible for ensuring that permissible limit values in the workplace are not exceeded. National standards should be in effect at the latest from 30 April 2008.

With arc welding, the main problem is the electromagnetic field around the welding and return cables. Alternating current, or a fluctuating direct current,

ESAB Welding Equipment AB
S-69581 Laxå Sweden
Made in Sweden

AristoArc 400

3~
IEC/EN 60974-1
EN 50199

16 A/21 V - 400 A/36 V

	X	35%	60%	100%
U_0= 78-90V	I_2	400 A	320 A	250 A
	U_2	36 V	33 V	30 V

3~ U_1 400V 50-60Hz | I_{1max} 38 A | I_{1eff} 22 A

AF | IP 23 | S

10.2 Example of a rating plate.

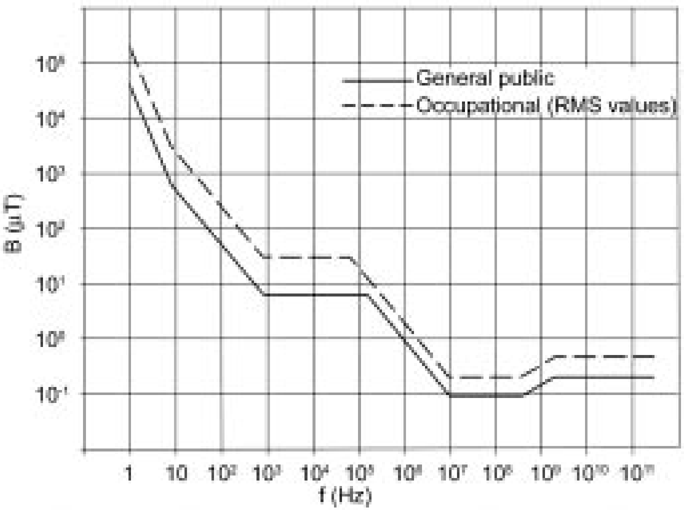
creates a magnetic field which in turn can induce currents in the human body. The most sensitive organs are the brain and heart. The induced body currents increase if either welding current amplitude or frequency is increased. Problems arise when the induced currents reach values similar to those of the body's own signalling system, i.e. in the nervous system. The limit values set in the directive are intended to provide protection against such immediate reaction risks: effects that might be caused by long-term exposure to magnetic fields are not considered in the directive.

The magnetic fields occur around conductors through which current flows. The magnetic flux density is measured in tesla (T). In air or other non-magnetic objects, the flux density is so low that the unit μT is normally used. A low value for the magnetic flux density for low-frequency fields is 0.2 μT, and it is unusual for this value to exceed 1 μT in a normal office environment.

The frequency of the field is important when it comes to its ability to transfer energy to the surroundings. So, in this way, heat or electric currents can be generated in surrounding objects.

10.3.1 ICNIRP guidelines

The EU directive refers to the ICNIRP Guidelines, which give reference values for time-variant electromagnetic fields, as shown in Fig. 10.3. ICNIRP is the



10.3 Reference values for magnetic fields as given in the ICNIRP guidelines. Higher values are permitted for professional activities, as such work is assumed to be performed under more controlled conditions.

International Commission on Non-Ionizing Radiation Protection. The values are based on known health risks in connection with current densities in body organs and, at higher frequencies, on the risk of dangerous tissue heating.

Figure 10.3 shows for occupational use a maximum value of 500 μT at 50 Hz and 30.7 μT at 1000 Hz.

10.3.2 The welder's situation

Welders belong to one of the occupational groups which are exposed to the highest field strengths. Arc welding requires high welding currents. The welding cables are often in close contact with the body.

A great deal of welding is performed with direct current. This applies, for example, to MIG welding. Pure direct current has no effect on the health risks but a normal welding current often has some pulsation component. The magnetic fields are highest when welding with pulsed arc, short circuiting arc or with AC current. High current welding with these applications may reach the ICNIRP reference value close to the welding cable. Very few cases are, however, reported where welders have noticed problems that can be attributed to the magnetic field.

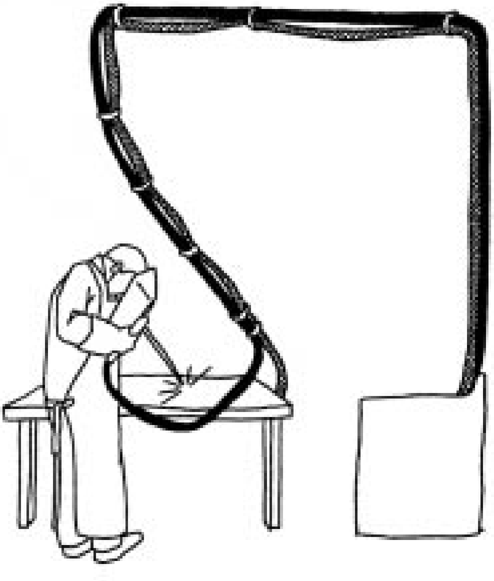
People with a pacemaker should be especially careful. It is unsuitable for them to be in the vicinity when resistance welding is in progress and, in some cases, even when some other type of welding with high currents is performed. Consult an expert physician.

10.3.3 Measures to reduce magnetic fields from welding current

A great deal can very definitely be achieved by passing on factual information about the health risks associated with welding. If there is a risk of injuries caused by the magnetic fields, it is probably far lower than that associated with many other situations during welding.

Mechanisation of the welding process, perhaps using robots, improves the welder's working environment in a number of ways. The following measures are recommended.

- Ensure that welding cables and return cables are run together whenever this is practically feasible (see Fig. 10.4).
- Avoid draping the cables over the shoulders or wrapping them around the body during welding.
- Use supports or counterbalance arms for the welding cables to keep them away from the body. The magnetic field strength falls rapidly with increasing distance from the cable.
- Welding with direct current is preferable to welding with alternating current.
- Persons with pacemakers or other implants should contact their doctor to find out whether the device can be safely used without risk of being affected by magnetic fields.



10.4 If the welding cable and return cable are kept close together their respective fields will cancel one another out.

10.4 Machine safety and mechanical protection

The moment we begin working with machines with moving parts, such as welding robots or cutting machines, we must be aware of the possible risk of personal injuries. To begin with, the design should be such that risks are avoided wherever possible. If it is not possible for practical reasons to eliminate the risks, appropriate protective measures must be implemented to guarantee personal safety. The appropriate action can be taken on several levels.

- Mechanical protection or guards/casing which provide direct protection. These protective devices should be sufficiently robust without impeding or limiting visibility or operation.
- If straightforward mechanical protection is not possible for functional reasons, the operator must be positioned outside the risk zone and some form of enclosure must be created around the equipment to reduce the risk of injury. The opening to the risk zone, such as a hatch, gate or service entrance, must have an interlocking device, which stops the machine in the event of unauthorised entry. The zone can be monitored with safety switches on hatches or gates, light bars for the service entrance or a pressure sensitive mat, which senses when someone is present. The enclosure and safety devices should not be designed in such a way that they are easy to bypass or deactivate.
- Protection may also be required to protect the operator from risks when work has to be performed inside the risk zone for some reason.
- Personal safety equipment, training, information and warning signs provide a warning about the risks which may still exist after the above action is taken.

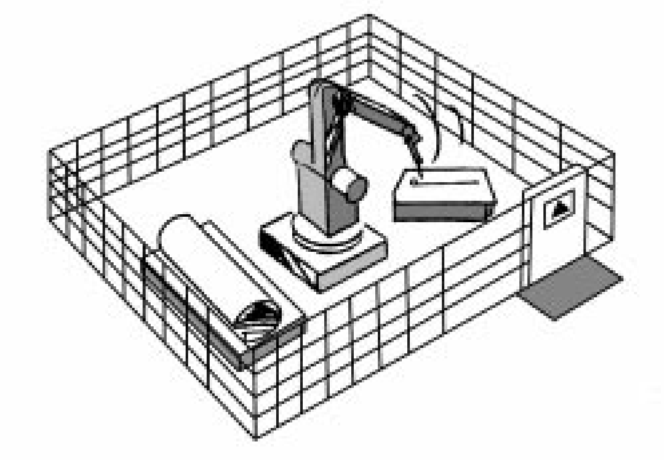
10.4.1 The EU's Machinery Directive

The Machinery Directive is a mandatory directive within the EU with which every new machine has been obliged to comply since 1 January 1995. According to the definition, a machine has at least one moving part and can operate independently.

The Machinery Directive specifies the basic safety requirements for machines. More detailed information can be found in what are known as the harmonised European standards (EN). Applying them is basically voluntary but, if a machine has been designed in accordance with these standards, it is also regarded as complying with the Machinery Directive. CE labelling indicates that a machine complies with the directive.

10.4.2 Robot welding stations

Robot welding stations are always surrounded by safety fencing (see Fig. 10.5), to ensure the necessary safety. Unauthorised persons must not enter the robot's working area when it is in use. Fencing is often high, with gates or openings



10.5 It is important to follow the safety requirements for machines.

protected by light beams that automatically stop the equipment if the beams are broken. Only appropriately trained programmers or service technicians are allowed to work within the robot's working area, and then only after taking special safety precautions. In addition, the stations include emergency stop devices that should preferably be easy to reset after operation.

10.5 Welding fumes and gases

On average, the fumes produced by MIG welding are less than those produced by the use of coated electrodes. The quantities are strongly affected by the welding parameters, and particularly by the current and voltage. The fumes originate from the electrode or from any surface coatings on the workpiece and consist of solid airborne particles, oxides of iron, manganese, chrome and nickel. Oil fumes are also formed if the workpiece is oily or greasy. Gases with possible health effects also evolve in the area of the arc. Examples of such gases are ozone and carbon monoxide.

The normal protective measures consist of good ventilation, preferably in the form of local extraction immediately above the weld, and attempting to avoid breathing in the direct fumes from the weld. Particular care should be taken in certain cases: in these situations, and also when welding in confined spaces where there is insufficient ventilation, it can be appropriate to use a fresh air breathing mask.

10.5.1 Fumes

Welding fumes are a result of the vapourisation and oxidation in the arc of different substances, resulting from the high temperature. The particles in these fumes are generally so small that they can reach the narrowest branches of the respiratory organs. These particles consist of oxides of iron, manganese, chrome and nickel, for example.

Normal protective measures include good ventilation, preferably as local extraction, and common-sense avoidance of breathing in the smoke from the welding process. Special measures should be taken in some cases:

- If unusually large amounts of fumes are produced. Cored wire containing flux, and being welded with high welding data, can produce substantial quantities of fumes.
- The fume from aluminium is suspected to affect the nervous system.
- The fumes produced when welding stainless steel contain chromium or nickel. MMA welding generates hexavalent chromium that may cause cancer and asthma-like problems. It can also be produced by MIG welding, although in lower quantities.
- Manganese may affect the central nervous system.
- Nickel may cause cancer and asthma.
- Iron oxides may cause irritation in the airways.

A number of different substances can be released from surface-coated materials:

- Welding galvanised steel produces substantial quantities of fumes due to the low boiling point of the zinc. Inhalation of these fumes can cause an ague-like response.
- Pressed steel sheet often has a film of oil, which forms smoke from the weld and as the heat spreads from the weld to other parts of the sheet.
- Material coated with lead paint can release lead and affect the central nervous system.
- Polyurethane paint or insulation can release isocyanates which can cause asthma.

It is essential to remove such coatings to a safe distance from the welding joint (see Fig. 10.6).

Occupational exposure limits

Most harmful substances have occupational exposure limits (OEL) which are regularly revised. The most common of these limit values specifies the average concentration which does not normally represent a health risk during eight hours of work a day (level limit value). A maximum exposure limit or short-term limit value is also specified for certain substances (see Table 10.1).

As the gases and particles which form affect the body in different ways, it is important that the regulations issued by the authorities and the instructions issued by manufacturers are followed in order to avoid ill-health. Material

10.6 The base metal must be exposed for at least 10 cm, sometimes even more, from the point of welding to avoid fumes and gases from paint or other surface treatment.

Safety Data Sheets (MSDS) are also available. On these sheets, the manufacturer has 16 points under which to provide detailed information.

Hygienic limit values (Table 10.1) specify the maximum concentration of some contaminant that is regarded as not presenting a health risk. They are expressed as average values. Some abbreviations are as follows:

MAC = Maximum Admissible Concentration
TLV = Threshold Limit Value
OEL = Occupational Exposure Limit.

Table 10.1 Hygienic limit values (Sweden, 2004) for some substances found in welding smoke

Substance	TLV (mg/m^3)
Inert dust	5
Iron oxide	3.5
Manganese	0.2
Fluorides	2
Chromates	0.02
Nickel compounds	0.1
Copper	0.2

10.5.2 Gases

The most common gases produced during welding are ozone, nitrous gases and carbon monoxide.

Ozone forms when the oxygen in the air reacts with the ultraviolet radiation from the arc. Ozone is a colourless gas, which is a powerful irritant which attacks the mucous membrane and the cell membrane. High concentration may appear when, for example, MIG welding aluminium at higher currents and with a high-radiancy arc. Note, however, that shielding gases are available that actively help to break down the ozone. Avoid welding in the presence of chlorinated hydrocarbon solvents (e.g. trichlorethylene): a chemical reaction can produce phosgene, which is poisonous and may damage the lungs.

Nitrous gases (nitrogen oxides) form when the nitrogen and oxygen in the air react with the hot arc and the hot base metal. These nitrous gases affect the lungs.

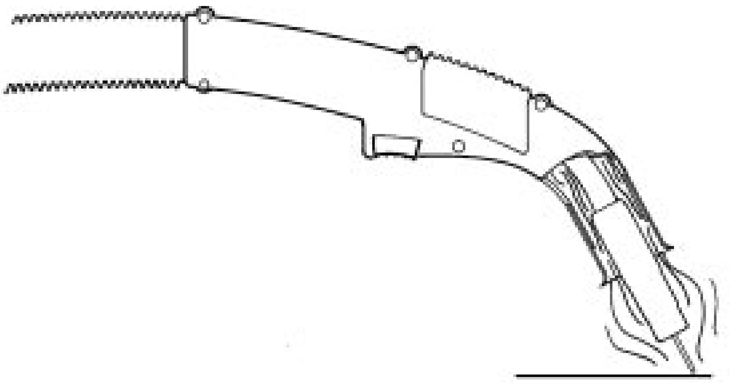
The use of CO_2 as shielding gas can produce carbon monoxide (CO) which, under unfavourable circumstances, can reach health-hazardous levels. CO affects the ability of the blood to absorb oxygen.

10.6 Ventilation measures

One should naturally avoid breathing in the smoke arising directly from the weld. When welding indoors, this means that some form of ventilation is necessary: the best is some form of spot extraction, capturing the smoke at source before it spreads into the surrounding air. There are various types of systems, depending on such factors as how mobile the welder needs to be.

A high-vacuum system uses relatively small-diameter extraction hoses and a fan similar to that of a vacuum cleaner, producing an air flow rate of about $100\,m^3/h$ and a negative pressure of about 100 kPa. The extraction point needs to be close to the arc, not more than 5 to 10 cm away. Systems of this type are used, for example, for MIG welding torches with integral fume extraction, as shown in Fig. 10.7. It should be possible to adjust the distance between the extraction point and the arc, in order to avoid disturbing the shielding gas. The risk of interfering with the shielding gas is greater in a confined space, when welding fillet welds or when welding inside corners. On the other hand, there is a risk of not capturing all the smoke in a more exposed situation. The best protection against these two problems is to provide a high extraction flow rate and to increase the distance between the extraction point and the arc.

Even with an effective spot extractor, some welding fumes will spread into the workplace. Fumes from the underside of the workpiece and fumes which develop after finishing are difficult to trap with spot extraction equipment. The general ventilation requirements should therefore be rigorous.



10.7 Welding torch with integral fume extraction.

Different measures can reduce the risk of exposure to dangerous substances.

- Use spot extraction when working indoors. The spot extraction equipment must be moved when long joints are being welded.
- Welding torches with integral extraction can remove most of the fumes before they reach the surrounding air (see Fig. 10.7). The position of the extraction nozzle should be adjustable, in order to avoid interfering with the shielding gas.
- When welding in confined spaces where there is a risk that the concentration of fumes and gases could be too high, the welder must use breathing protection with a supply of clean air, which makes him or her independent of the surroundings (see Fig. 10.8).
- To avoid fumes and gases from paint or some other surface treatment, the base metal must be exposed at least 10 cm from the point of welding (see Fig. 10.6).

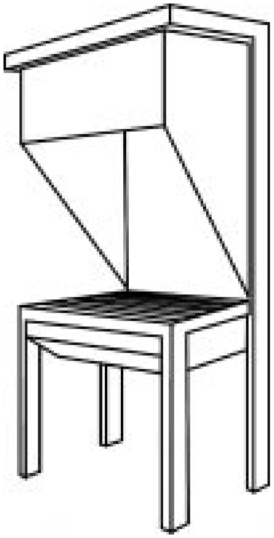
It should be borne in mind, if using portable welding smoke filters, that they deal primarily with the visible smoke, i.e. particulates. If welding is being carried out in an enclosed space, it is important to place the filter outside, in order to avoid building up dangerous concentrations of toxic gases.

The most popular extraction arrangement is the use of adjustable extraction arms, as shown in Fig. 10.9. The use of a low-vacuum system (about 10 kPa) with higher air flow rates (about 1000 m/h) can provide extraction from a somewhat greater distance, although the welder must be careful to keep the arm close to the weld position, which in practice means not more than 30–50 cm from it.

It can be a good idea, when welding smaller parts, to arrange an extraction above the welding bench, as shown in Fig. 10.10. This requires a higher air flow rate, of about 5000 m/h, and the extraction should be positioned slightly above/behind the bench. Performance is considerably improved if the extraction is 'screened' to prevent it pulling air from where there is no need to do so.

10.8 When welding in confined spaces where there is a risk that the concentration of fumes and gases could be too high, the welder must use breathing protection with a supply of clean air.

10.9 Flexible fume extraction arm.



10.10 A welding bench with fume extraction.

Arranging an extraction in a welding jig means that it can be positioned close to the welding zone, and can extract the smoke with only a modest air flow.

10.7 Radiation

The arc – and the molten pool to some degree – is a strong source of radiation in the infrared (IR), visible and ultraviolet (UV) ranges of the spectrum. Sharp variations in radiation can occur, depending on the current level and many other factors. Special protective glasses must be used for the eyes, and all skin should be protected by fully-covered clothing. The radiation can also be reflected by surrounding surfaces and may expose skin from an unexpected direction. The visible light has most often just a dazzling effect and may temporarily affect the vision. IR radiation can cause damage to the retina and the lens (cataracts).

Arc eye (flash) is a strongly irritating inflammation of the cornea of the eye, caused by ultraviolet radiation (risk is largest at wavelengths of 280–290 nanometers). It takes the form of pain and irritation, starting about six hours after exposure. However, it normally subsides naturally, and has no permanent effects. It can be avoided by using welding goggles, and also by taking care to screen off the welding position and prevent reflections of the arc that could be seen by others in the vicinity.

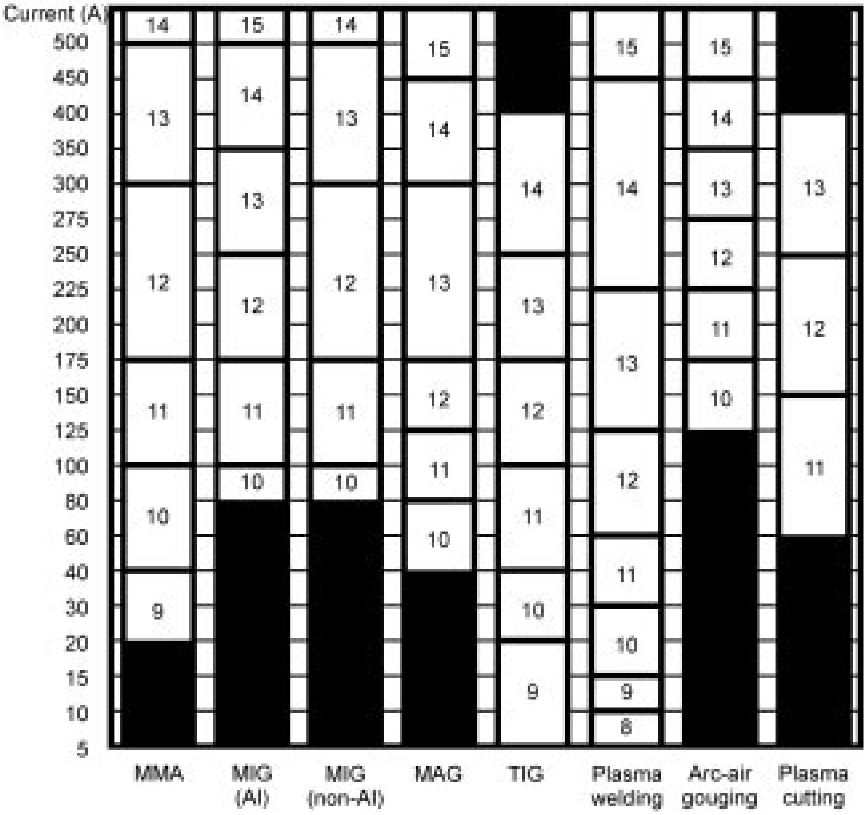
Skin damage. UV radiation can hurt unprotected skin. The damage resembles stinging sunburn.

10.7.1 Preventive actions

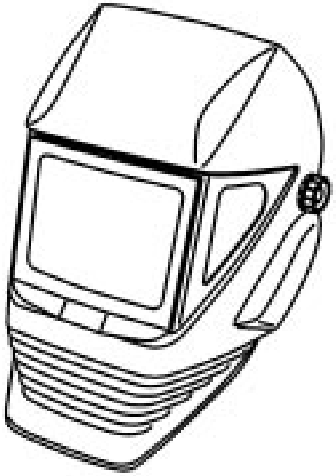
A welding screen or welding helmet with a standardised glass visor, is advised. Recommended filter shade levels are given in Fig. 10.11. The particular level required depends on the type of welding process and the welding current, providing protection against ultra-violet, visible and infra-red radiation as necessary. The following are the main means of protection:

- A welding helmet with a window and side guards for use during slag removal.
- Welding overalls or some other protective clothing with a leather apron.
- Leather gauntlets, without rivets or other metal components, on both hands.

As an alternative to ordinary protective helmets, there are welding helmets with liquid crystal screens that sense ultraviolet radiation and switch extremely rapidly between clear and dark (see Fig. 10.12).



10.11 Recommended filter shade levels for protective glass filters. More detailed information is given in the standard EN 169.



10.12 A welding helmet with an auto-darkening filter (ESAB).

Contact lenses

Wearers of contact lenses will, of course, also want to wear them while welding. If the eye is exposed to strong thermal radiation, the rise in temperature of the lenses may accelerate their drying out. Although soft contact lenses are kept soft by moisture in them, the risk of their drying out so much that they become difficult to remove is not great. Nevertheless, if this should happen, it is best to re-moisturise them in position, so that they loosen before being removed.

Ordinary welding goggles also provide effective protection against thermal radiation.

Thermal radiation is a major problem at some welding workshops. This applies in particular when the welding is performed on preheated objects. The following points should be taken into consideration when welding at elevated working temperatures.

- The workplace should be well ventilated.
- The object should have effective thermal insulation.
- Suitable protective equipment, such as heat-insulated gloves, should be used (see Fig. 10.13).

As working in high temperatures imposes a strain on the body, suitable breaks in the welding must be planned.

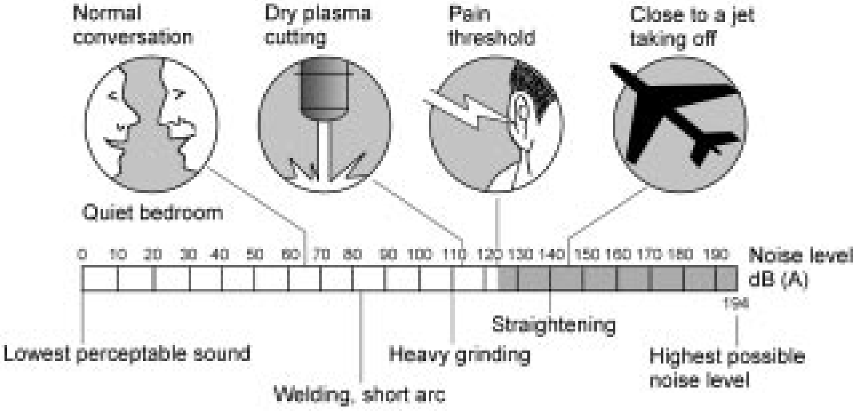
10.8 Noise

Short arc welding is relatively noisy, producing noise levels up to 80 dB. Welding is often also accompanied by noisy grinding, slag removal or

10.13 Protective clothing for thermal radiation and spatter.

straightening work in the vicinity (see Fig. 10.14). By using a suitable welding process, shielding gas and welding technique that minimises grinding and slag removal, the noise problem can be reduced.

There is thought to be a risk of permanent hearing impairment if people are exposed to 85 dB(A) for more than eight hours per working day. As a rule of



10.14 Some sources of noise as a reference to the dB scale.

thumb, it would be true to say that the noise level is unacceptable when it is difficult to conduct a conversation.

10.8.1 Measures to reduce noise

To begin with, an examination should be made to see whether the process or production set-up can be modified to avoid the sources of noise.

- Using a suitable welding process, welding data, shielding gases and welding technique can minimise grinding and slag removal or, at best, eliminate them completely.
- Use quieter tools for grinding and removing slag.
- Screen off noisy work and take measures to reduce reverberation in working areas by putting up noise absorbers.
- Use ear protectors if the noise is disruptive or if there is a risk of hearing damage.

Hearing tests should also be conducted at regular intervals.

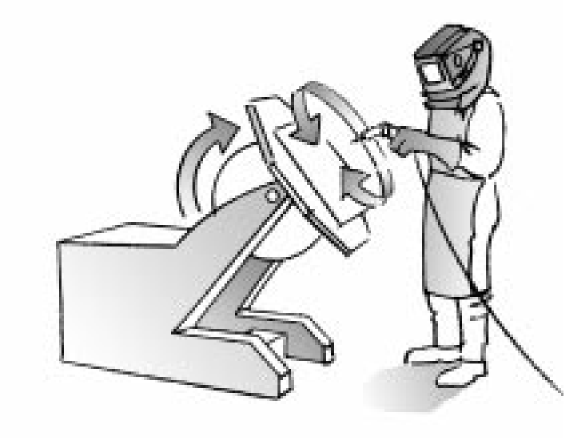
10.9 Ergonomics

Welding thicker, heavier and/or larger parts manually and during assembly welding involves more static loading on the welder. The welding times are longer and the weight of the equipment is greater. In addition, the working position in this case is dependent on the position of the weld joint. Working with the hands in a high position at or above shoulder level should be avoided whenever possible. Overhead welding is unsuitable from an ergonomic angle.

Welding small items in fixtures is often characterised by many short welds, with monotonous, unchanging movements between them. When planning a workplace, the working height plays an important part in creating the correct working position. In this context, positioners and lifting tables can be very useful.

10.9.1 Measures – technical devices and equipment

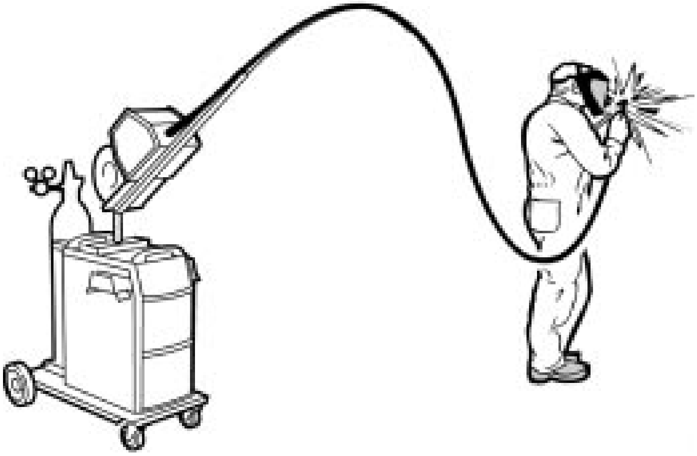
When planning a workplace, the working height plays an important part in creating the correct working position. In this context, positioners and lifting tables can be very useful. The working position is partly determined by the welder's need to have his or her eyes close to the workpiece to be able to see the molten pool clearly while welding. If the working height is too low, the welder has to bend to see properly. A chair or stool might then be very useful. Working with the hands in a high position at or above shoulder level should be avoided whenever possible.



10.15 A positioner for the workplace.

It is also a good thing if the workpiece is placed in a positioner and is positioned to ensure the best accessibility and height (see Fig. 10.15). A more comfortable working position can be created and, at the same time, welding can be facilitated as the joint is in the best welding position.

In conjunction with heavier welding, the gun and hoses are also heavier. A counterbalance support can provide valuable help in this situation (see Fig. 10.16). Lifting the hoses off the floor also protects them from wear and tear, as well as facilitating wire feed.



10.16 A counterbalance arm reduces the weight of the hose bundle over the entire working area.

When MIG welding small items in fixtures, there is a risk of industrial injury as a result of the monotonous, unchanging movements. The gun is often supported by holding one hand against the workpiece.

Roller beds can be used for welding tubes or other cylindrical items. A hook or some other device on which the welding gun can be placed when it is not in use is another valuable piece of equipment.

10.10 Spatter

In some cases, the spatter produced by welding can cause discomfort and even burns. The risks increase in connection with overhead welding or if the welding is performed in confined spaces where the welder may even have to lie down to obtain better access to the object they are welding.

10.10.1 Preventive action

By using suitable welding parameters, a suitable shielding gas with a high argon content and the right working technique, it is possible to avoid overly large drops of spatter. Fine spatter is normally fairly harmless.

To avoid these problems, it is important to use fully-fitting clothing made of a suitable heat-resistant material and tested to EN 470-1.

10.11 Fire risks

Welding or thermal cutting are common causes of fire. Experience shows that the risks are greatest in connection with temporary work in premises or areas not normally intended for welding (see Fig. 10.17). If such work has to be carried out, the person responsible for safety must decide on what protective measures need to be taken.

- Cleaning and removal of combustible materials in the risk zone.
- Any holes or gaps in combustible materials used in the building must be covered or sealed so that weld spatter or sparks, e.g. from gas cutting, cannot find their way in.
- Use water to dampen the area before and perhaps after work.
- Screen off the area.
- Ensuring that adequate extinguishing equipment is available.
- Monitoring and after-inspection (one hour) by a fire guard.
- Make sure that staff are sufficiently familiar with the regulations and the ways in which risks can be avoided.

Fires caused by welding and cutting are largely due to a lack of knowledge, carelessness and insufficient protection. Training and effective protection programmes are essential in this context.

10.17 Risks are greatest in connection with temporary work in premises or areas not normally intended for welding.

At temporary workplaces, welding or cutting is often used. This generates a great deal of heat that has to be conducted away and the risk of relatively large molten particles and sparks which can cause fires is greater. Workplaces where the risk of fire is high are particularly dangerous welding sites, e.g.:

- Places where flammable substances, such as petrol and oil, or flammable gases are handled.
- Premises containing packaging material or timber goods.
- Construction sites where sparks can more easily spread into areas that are not readily accessible, such as walls made of wood or containing flammable insulation.

When working in dangerous environments of this kind, welding inspections must always be conducted. In some cases, the approval of the municipal safety officer and insurance companies must be obtained.

10.11.1 Slow combustion

At other places, where the material is perhaps less flammable, ignition can begin with slow combustion. It can then develop into a fire with open flames. A relatively long period can pass before the fire is discovered and, if the seat of the fire is also difficult to reach, extinguishing the fire is more difficult, even if fire-fighting equipment is available.

10.11.2 Development of fire in different environments

Fires in PVC plastic, which is often found in electrical cables or other interior design materials, generate hydrogen chloride vapour which, together with the moisture in the air, creates hydrochloric acid. This is a powerful irritant and it is also highly corrosive when it comes to metals. In addition, it can damage sensitive electronic equipment.

There may be a risk of explosion when flammable substances such as petrol, oil or paraffin are heated. If they do not ignite directly, there is a real risk of explosion as they first vapourise.

Remember that the heat produced by welding or cutting a pipe can be conducted into a nearby wall and cause a fire, even if the temperature is relatively low. A sufficiently large spark from welding, cutting or even grinding could cause a fire, even if it is not red-hot.

Fires in enclosed spaces such as walls and insulation can develop relatively slowly. Always call the fire brigade if a fire of this kind occurs.

Call the fire brigade even if it appears that the fire has been put out, as it is important to check that no source of slow combustion is left.

10.11.3 Preventive action

If welding or cutting has to be performed in places where there is a risk of fire, a safety officer should assess the preventive action that needs to be taken.

10.12 Bibliography

Handling of non-consumable tungsten electrode containing thorium oxide, Schweissen und Schneiden, no. 11 1999.

Hazardous substances in welding and allied processes, Metall-Gerufsgenossenschaften.

Welding adds hazards to work in confined spaces, IIW 1998.

Welding and cutting – risks and measures. ESAB AB, Göteborg Sweden.

Weman, K. (1994) *Health hazards caused by electromagnetic fields during welding.* Svetsaren No. 1.

10.12.1 Directives and standards

Amended proposal for a Directive of the European Parliament and of the Council on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) (18th Individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC).

EN 166 *Personal eye protection-specifications.*

EN 169:1992 *Filters for personal eye protection equipment used in welding and other similar operations*.

EN 470-1 *Welders clothing.*

IEC 479-1 *Effects of current on human beings and livestock. Part 1.*

IEC 479-2 *Effects of current passing through the human body. Part 2*.
IEC 62081:1999 *Arc welding equipment – Installation and use EN 60974-1:1998 Arc welding equipment – Part 1: Welding power sources.*
IEEE Std C95.6-2002 – *Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Fields, 0–3 kHz.*
Machinery Directive 89/392/EEC (plus amendments).
Personal Protective Equipment 89/686/EEC (plus amendments).

11

Reducing costs in MIG welding

G LINDÉN, Air Liquide Gas AB, Sweden

11.1 Introduction

The choice of a particular welding process is usually made on cost as well as technical terms. Technical limitations can be such as the type of material, its thickness, the type of joint required and/or welding position, i.e. factors directly linked to the capabilities of the particular welding method. In addition, there are limitations that may be imposed by special quality requirements, production resources in the factory, the work environment and so on. Despite potential benefits, a company may not have been able to invest in new welding equipment or a new welding method, with all that is involved in terms of equipment cost, training of personnel and bringing the new facilities into production.

As a result, the general determining factor in deciding on a particular welding process is usually cost – that is, to choose a process that produces the required quality at the lowest possible cost. This is assisted by a method of making welding cost calculations by means of a refined internal cost analysis procedure that calculates the costs that are specific to the welding element of the work. Traditionally, these costs consist of those for labour, consumables (which include shielding gas), equipment and energy. There are, of course, many other costs, such as those for joint preparation, inspection, painting, etc., all of which must be considered. The following material considers only the costs connected to the job performed by the welder.

In this chapter the general welding cost calculations are concentrated on MIG/MAG welding. There are, anyway, many different alternative possibilities with manual, mechanised or robotic welding as well as electrode types and high productivity methods.

Internal cost calculation can be used to arrive at the cost of welding a product, and also for comparisons between different procedures or for investment in new equipment, e.g. for the introduction of automation. It can also be used when evaluating various ways of reducing welding costs.

The calculations according to the model presented can be performed manually, or there are also more or less comprehensive computer programs that assist the work and so make it easier to compare a larger number of alternatives. Some programs include databases for materials, filler materials, hourly rates, guide values for welding parameters and so on, which further assists the work.

It is important to realise that the accuracy of the calculations can never be better than the quality of the input data. Experience from earlier calculations, for which true costs have been obtained by post-production costing, is therefore important in ensuring that cost estimates are reliable.

11.2 Important economical advantages of MIG/MAG welding

MIG/MAG welding has become a very important and frequently used welding method. Before the detailed cost calculation procedures some advantages directly related to the costs will be summarised.

MIG/MAG welding can operate over a very wide range of deposition rates with a small number of wire sizes. That means that there is normally no need to change the wire size very often. Both solid and flux-cored wires can be used.

The deposition rate can be higher than comparable methods and the welding speed can therefore be high. The deposition efficiency is high, which means only a minor part of the solid wire or the metal-cored wire is lost as spatter. For the flux-cored wires the amount of slag is greater.

The feeding of the wire is automatic which is advantageous both for manual welding and for mechanised/automatic and robotic welding. A disadvantage can be that manual welding of long welds may be taxing for the welder.

All high-speed MIG/MAG welding techniques normally require automatic welding equipment. Robots have become the most important device for moving the welding gun. The possibilities with robotic welding have proved to be a real break-through in the use of MIG/MAG welding.

The amount of slag is low and this means that the post-welding operations can be omitted in many cases or require fairly small efforts from the welder.

11.3 Some welding cost concepts

Welding costing uses a number of concepts, as defined below.

The *deposition rate* is the weight of weld metal melted into the joint per unit of time (while the arc is struck), and is usually expressed in kg/h.

For MIG/MAG welding with solid wires, diagrams and/or tables of deposition rates for different wire diameters and welding currents are available. The welding parameters have to be determined from the actual situation, e.g. welding position, material thickness, joint type. If the wire feed speed is known it can be used to calculate the deposition rate directly. In that case the deposition efficiency must be accounted for.

Table 11.1 Typical values for comparative cost calculations

	Operator factor	Deposition efficiency
MIG/MAG, solid wire	0.25–0.90	0.95
MAG, flux-cored wire	0.25–0.90	0.85
MAG, metal-cored wire	0.25–0.90	0.95

The *deposition efficiency* indicates the proportion of the gross weight of filler material actually used that is converted to useful weld metal. Flux-cored electrodes form slag, and so the deposition efficiency is considerably less than 1. Solid wires and metal-cored wires have higher deposition efficiencies but some material is lost as slag or spatter. If the deposition rate is calculated from the wire feed speed, it is necessary to multiply the result by the deposition efficiency in order to compensate for slag or spatter losses.

Typical values of deposition efficiency are given in Table 11.1.

The *weight of weld metal* is calculated from the details of the joint as shown on the welding drawings, which gives the volume of weld metal, multiplied by the density of the material which, for steel, is 7.8 kg/dm^3. The cross-sectional area of the weld, and its length, give the theoretical volume of weld metal. A fillet weld with a throat thickness of 4 mm and a length of 1 m has a weld metal volume of 16 cm^3. In practice, this value may need to compensate for excess deposition, gaps, etc., which increase the volume, and/or shrinkage, which decreases the volume. Tables are available that give the weld metal volumes for various types of joints. The previously mentioned computer programs automatically calculate the volume from the given joint data.

The *job time* is the time that it takes to carry out a particular welding job, and includes the setting-up time and the operation time. The *setting-up time* is the time required to set up and start the new work. In the case of mass production processes, this time will be incurred only in connection with the first workpiece to be produced. The *operation time* is the time taken for welding each workpiece, and includes:

- The *arc time*, i.e. the time for which the arc is actually struck.
- The *additional time* directly connected to the arc time, i.e. the time taken by replacement of the filler wire, slag removal, cleaning gas nozzles, etc., and directly related to the welding.
- The *handling time*, i.e. the time for handling workpieces, preparation prior to welding, such as tack welding, etc. This time is very dependent on working practices and procedures.
- The *contingency allowance*, i.e. time that cannot be directly related to the welding, and which is often allowed for by a percentage addition.

The relative proportions of the total made up by the above times will vary, depending on the types of items produced, the way in which the work is carried out, the availability of ancillary equipment, the amount of mechanisation and so on.

The *arc time* is the time for which the arc is actually burning, and can be arrived at in various ways. Tables and diagrams from the literature and from suppliers give guide values that can be used in cases where a company does not have experience of its own to draw on. A company's own values, of course, have the advantage of applying exactly the right value for the company's own particular situation and circumstances. The *arc time* can also be calculated from the weight of weld metal divided by the deposition rate.

The *operator factor* expresses the relationship between the time for which the arc is struck and the total welding working time. It has sometimes been incorrectly used as a measure of productivity, i.e. assuming that a high operator factor indicates a high productivity. However, using a welding method having a higher welding speed will reduce the arc time. If other times are unchanged, this will mean that the operator factor is reduced, despite the fact that the work has actually been performed more quickly. If the company has experience-based values of operator factors for some particular types of welding, the total job time can be calculated by dividing by the operator factor. Typical operator factors are shown in Table 11.1. The low values are related to manual welding and the high ones to automatic welding. For manual welding it is normal not to reach higher than 25–35%.

Since the operator factor is very important for the total operation time, especially in manual welding, big efforts are needed not only to reduce the arc time by more efficient welding procedures but also to simplify and reduce the time for all the other activities.

11.4 Cost calculation

The *labour cost* is obtained by multiplying the *operation time* by the hourly cost. Companies know their own hourly costs, which are made up of hourly direct wage costs, employers' social insurance charges, holiday pay, etc. The hourly cost often includes a share of common costs in the form of a percentage addition.

The cost of consumables needed for welding is referred to here simply by the umbrella name of *cost of filler materials*.

- Electrode consumption can be calculated from the weight of weld metal divided by the deposition efficiency. Kilogram cost of electrodes is company-specific.
- Consumption of shielding gas can be calculated from the arc time multiplied by the gas flow rate in l/min. The gas cost (euro/l) depends on factors such as the method of supply/delivery (gas cylinders, bulk delivery), and is specific for the company.

Machine cost can include costs for welding equipment, mechanisation equipment, special handling equipment and so on, and can be considerable if it includes automation and/or robot equipment. The hourly cost of the equipment can be calculated from the costs for depreciation, interest and maintenance, together with an estimate of the annual use time. The details of this calculation, and of the elements to be included, vary from company to company. The machine costs for a particular welding job can be calculated from the hourly machine cost and the operation time.

The *energy cost* can be calculated from the arc time and power demand during welding, possibly with the addition of an allowance for no-load operation. It is not normally necessary to allow for the uncertainties that have to be considered for the other costs. Energy costs vary usually amount to a few percent of the total costs.

A summary of the formulae used in the cost calculation is shown in Fig. 11.1.

Comparison of all the above costs shows that it is the labour cost that is by far the highest for manual welding. A typical example from welding plain carbon steel is shown in Fig. 11.2. The cost of filler materials becomes more significant when welding expensive materials such as stainless steel. Machine costs become significant only when automated and robot welding come into the picture. Measures to reduce costs are therefore concentrated on reducing the operation time when the welding is done manually.

Labour cost

Wages: $$\frac{\text{Weld metal (kg)} \times \text{Hourly cost (euro/h)}}{\text{Deposition rate (kg/h)} \times \text{Operator factor}}$$

Cost of filler materials

Wire: $$\frac{\text{Weld metal (kg)} \times \text{Wire cost (euro/kg)}}{\text{Deposition efficiency}}$$

Gas: $$\frac{\text{Weld metal (kg)} \times 0.06 \times \text{Gas consumption (l/min)} \times \text{Gas cost (euro/m}^3\text{)}}{\text{Deposition rate (kg/h)}}$$

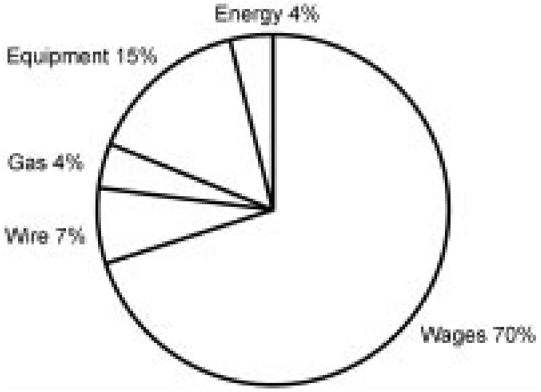
Machine cost

Equipment: $$\frac{\text{Weld metal (kg)} \times \text{Machine cost (euro/h)}}{\text{Deposition rate (kg/h)} \times \text{Operator factor}}$$

Energy cost

Electricity: Energy consumption (kWh) × Energy cost (euro/kWh)

11.1 Formulae for calculating welding cost.



11.2 A typical cost distribution for manual MIG/MAG welding (AGA).

11.5 Throat thickness

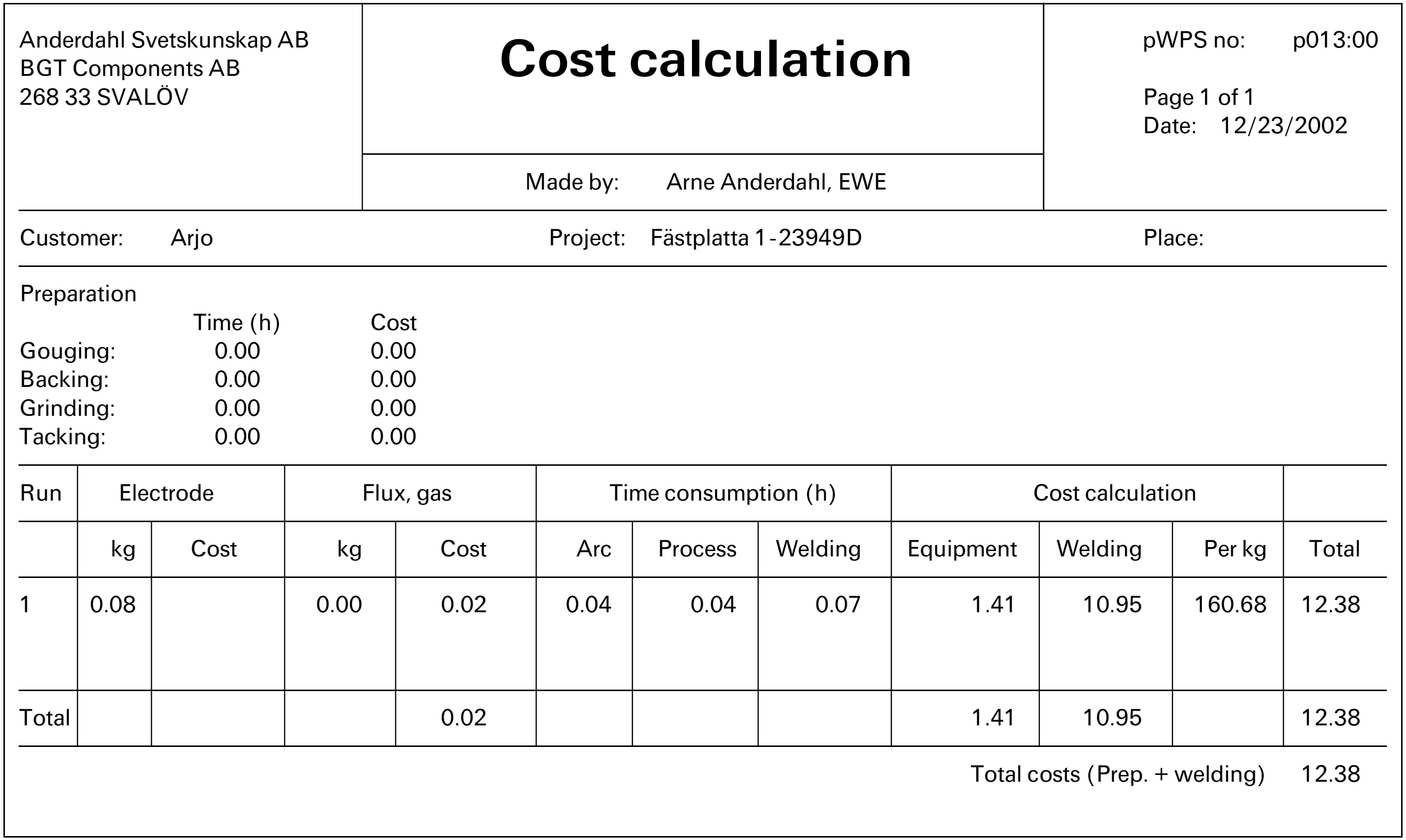
The throat thickness in fillet welds decides the amount of filler material and also greatly influences the welding costs. If the penetration can be taken into account when the strength is calculated it is possible to save costs. The throat thickness for a symmetrical fillet weld can be calculated by the following relation.

$$a = \sqrt{\frac{v_e}{v_1} \cdot \frac{k \cdot \pi}{4}}$$

where a = Throat thickness
v_e = Wire feed speed
v_1 = Welding speed
k = Deposition efficiency

11.6 Computer programs for welding cost calculations

Various types of computer programs for calculating welding costs are available. The simpler ones lack databases of filler materials, additional times, etc., but are cheap and user-friendly. At the other end of the scale is the Weldplan program (developed by the FORCE Institute, Denmark). It can be used to produce a complete specification of the work, which then forms the starting point for the cost calculations. Figure 11.3 illustrates a calculation using the program. The program can also produce an operations list, itemising operations to produce a total manufacturing cost.



Anderdahl Svetskunskap AB
BGT Components AB
268 33 SVALÖV

Cost calculation

Made by: Arne Anderdahl, EWE

pWPS no: p013:00

Page 1 of 1
Date: 12/23/2002

Customer: Arjo

Project: Fästplatta 1-23949D

Place:

Preparation

	Time (h)	Cost
Gouging:	0.00	0.00
Backing:	0.00	0.00
Grinding:	0.00	0.00
Tacking:	0.00	0.00

Run	Electrode		Flux, gas		Time consumption (h)			Cost calculation			
	kg	Cost	kg	Cost	Arc	Process	Welding	Equipment	Welding	Per kg	Total
1	0.08		0.00	0.02	0.04	0.04	0.07	1.41	10.95	160.68	12.38
Total				0.02				1.41	10.95		12.38

Total costs (Prep. + welding) 12.38

11.3 An example of a welding cost calculation, using the Weldplan program.

11.7 Methods of reducing welding costs

One of the most important reasons for making cost calculations is to identify ways in which manufacturing costs can be reduced. Costs are influenced right from the design stage, with further input factors all the way through to production. Some examples are given below.

The biggest cost in manual welding is the *labour cost*. This is directly related to the total job time. One way of reducing it is to introduce mechanisation and automation, described below.

The various parts of the total job time can be affected: a welding process with a higher deposition rate reduces the arc time; optimising the welding parameters means fewer disturbances and less spatter; welding equipment with high reliability reduces down-time. Equipment to hold or manipulate the workpiece to provide a good welding position assists welding. Planning of the work, too, is important, as often only 30% of the total time is productive arc time. It can sometimes be possible to avoid making unnecessary welds, and/or to use other production processes such as bending.

The design stage specifies the joint design and throat thickness of fillet welds. The joint design can be such as to minimise the amount of weld metal required, naturally subject to the necessary performance requirements. Too large a throat thickness always results in more weld metal than is needed: a throat thickness of 5 mm uses 56% more weld metal than does a throat thickness of 4 mm. It is also important to plan joint preparations, bringing together and holding the parts and welding so that no more weld metal than necessary is deposited: this will also have the additional benefit of reducing welding deformation. If, in addition, the penetration of the fillet weld can be utilised to reduce the nominal throat thickness, there will be a further reduction in the quantity of weld metal.

The use of *filler materials* can also be influenced, although this cost needs to be related to the labour cost. If the labour cost can be reduced by more efficient welding, reduction of preparation and finishing, such as spatter removal, avoidance of two-sided welding, fewer weld beads, improved quality etc., additional cost for filler materials or shielding gases can be justified.

Bear in mind, too, the overall production process. The correct quality of materials, fillers, careful joint preparation and bringing together of parts all assist welding, reducing the overall time and having the least possible effects on other processes. A properly made weld generates fewer problems of inspection and fewer corrections.

11.8 Mechanisation, automation, robot welding

Welding efficiency can be improved by the use of varying degrees of mechanisation. A certain level of mass production, or repeated production, is usually necessary, although various types of mechanisation equipment can be justified even with small batches. The introduction of mechanisation will alter the proportions between the various cost elements that make up the whole.

New high-productivity welding procedures as described in Chapter 8 require robots or automatic equipment with advanced control of the process and the movement of the welding gun.

Setting-up times are likely to be longer, particularly with more advanced automation. If manufacturing cost is to be viable, the cost of the setting-up times must be spread over a number of workpieces. The total savings emanate from lower operation time per item. Each welder can also produce more through use of the equipment, although the machine cost will be higher, reflecting the use of the advanced equipment.

Quality control costs are likely to be reduced, as production is more carefully managed when the equipment has been correctly set up. However, training and running-in will be needed, which introduces extra costs. Maintenance costs will probably also increase, in connection with the use of more complicated equipment.

Properly installed and used mechanisation/automation/robot processes improve working conditions in both physical and work content terms. Better utilisation of capital bound in products and stock is another positive factor, resulting from the ability to tailor manufacture to suit actual needs.

12

MIG welding of uncoated and surface coated steel

T NILSSON and A SKIRFORS, SSAB, Sweden

12.1 Introduction

The most important material used in MIG welding is steel either unalloyed or low-alloyed. In this book, MIG welding is, for simplicity, used for both MIG and MAG welding. For steel all shielding gases used are active gases. Another important type of steel is the stainless steel with high amounts of alloying elements. The stainless steel is discussed separately in Chapter 13.

The trend today is to use steels with high strength in a lot of different applications. In many cases this also means that the sheet thickness will be lower leading to more lightweight constructions. In order to improve the corrosion resistance coated steels are more often used, especially in the automotive industry. A combination of good formability and high strength can be achieved with the new advanced steel making and rolling processes available today in the steel industry.

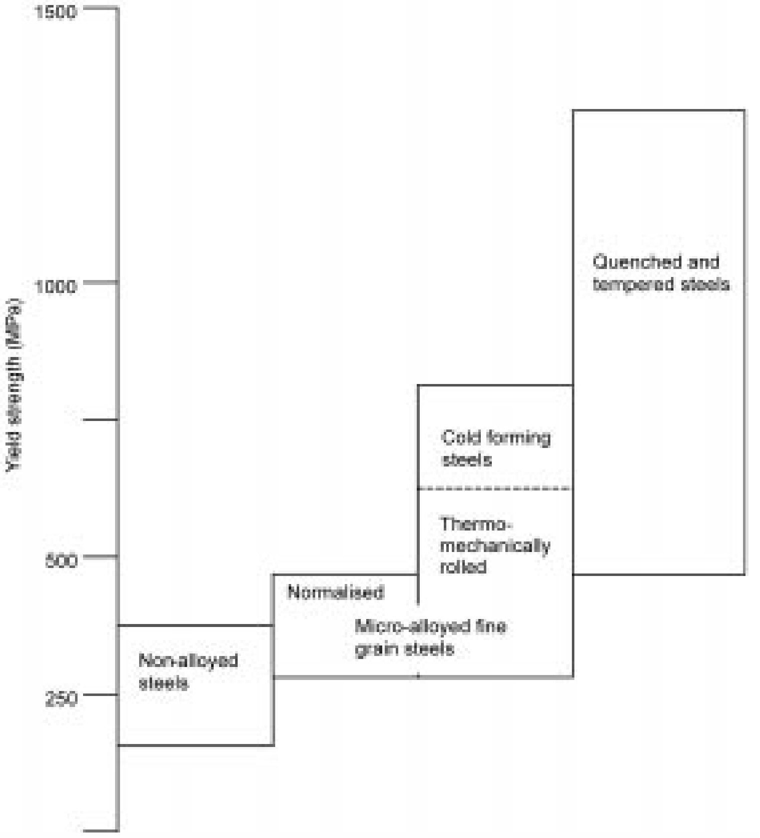
In this chapter MIG welding of different types of steel will be presented. Both new types of high strength steels and coated steels are included.

12.2 Structural steels and pressure vessel steels

Hot rolled structural steels and pressure vessel steels are widely used in many applications. These steels are standardised from 3 mm plate thickness and have a minimum guaranteed yield and tensile strength. The steels have, in general, very good weldability. The most important properties are normally strength, toughness and weldability.

Most of the steels are standardised; however, some steels that are not standardised are also presented in this chapter. That includes newer high strength steels and quenched abrasive resistant steels. Abrasive resistant steels are a type of steel that is growing very fast in importance. These steels are used more and more in applications where structural strength and abrasive resistance are combined.

Figure 12.1 shows schematically the yield strength for different groups of steels for welded structures.



12.1 Approximate yield strength for different groups of steels for welded structures.

12.2.1 Structural steels

Non-alloy structural steels

Non-alloyed steels are most often delivered in the as rolled condition, even if the normalised condition is also used. C and Mn are the main alloying elements. The steels are standardised in EN 10025-2 with minimum yield strength of 185–450 MPa. S235, S275 and S355 are the most common steels grades.

Normalised fine grain structural steels

Normalised and normalised rolled structural steels are standardised in EN 10025-3 with minimum yield strength of 275–460 MPa. By the normalising process, which consists of heating to typically 900 °C followed by air cooling, a fine grain 'normalised' structure is formed. Decreasing grain size increases both the strength and the toughness. Micro-alloying elements like V, Nb and Ti are also often used to achieve the aimed strength level and to improve the weldability.

Thermomechanical rolled fine grain structural steels

By thermomechanical rolling a very fine grain microstructure can be achieved by controlling the process parameters during rolling (TM, TMCP). Thanks to the rolling process high strength can be achieved with a relatively low carbon equivalent. These steels are standardised with yield strength of 275–460 MPa in EN 10025-4. The chemical compositions of TM-steels are characterised by low carbon contents. Micro-alloying elements like V, Nb and Ti are also often used to increase the strength even further.

Thermomechanically treated steels generally have good strength, toughness and weldability. Typical applications are welded structures like buildings, bridges, excavator arms and structures in the offshore industry.

Except for the standardised steels there are grades available with higher yield strength, 500 MPa is the most common strength level.

High strength quenched and tempered steels

Very high strength can be achieved by a quenching and tempering process. By quenching, a very hard and fine grain martensitic microstructure is formed. Quenched and tempered structural steels with yield strength from 460 up to 960 MPa are standardised in EN 10025-6. The steels fulfil the requirements of impact toughness for temperatures from 0 °C down to −60 °C.

Quenched and tempered steels are mainly used in load carrying structures having very high demands on low weight. Mobile crane booms and chassis are typical applications where very high strength steels can be used to decrease the weight and increase the loading capacity of the crane.

Except for the standardised steels there are company-specific grades available with as high a yield strength as 1300 MPa, for example WELDOX 1100 and 1300. These steels are normally tempered at such a low temperature that they cannot be subjected to PWHT or flame straightening. These products are extreme but even for standardised quenched and tempered steels the manufacturers' recommendations should be considered.

High strength steels for cold forming

These high strength steels have better bendability than conventional structural steels. The steels are often used in the transportation area where lower weight or higher loading capacity will lead to an improved economy. The steels are normally produced in hot strip mills and are delivered as thermomechanically

Table 12.1 Mechanical properties of high-strength steels for cold forming according to EN 10149-2

Steel designation		Strength		Elongation		Bending at 180
Steel name	Steel number	R_{eH} N/mm^2 min[1]	R_m N/mm^2 min–max[1]	Nominal thickness (mm) < 3 A_{80} min	> 3 A_5 min	minimum mandrel diameter[2]
S315MC	1.0972	315	390–510	20	24	0t[3]
S355MC	1.0976	355	430–550	19	23	0.5t
S420MC	1.0980	420	480–620	16	19	0.5t
S460MC	1.0982	460	520–670	14	17	1t
S500MC	1.0984	500	550–700	12	14	1t
S550MC	1.0986	550	600–760	12	14	1.5t
S600MC	1.8969	600	650–820	11	13	1.5t
S650MC	1.8976	650[4]	700–880	10	12	2t
S700MC	1.8974	700[4]	750–950	10	12	2t

[1] Longitudinal test pieces
[2] Transverse test pieces
[3] t = thickness in mm of test piece for bend test
[4] For thickness > 8 mm the minimum yield strength can be 20 N/mm^2 lower

treated steels. For some strength levels normalised or normalised rolled steels can also be used. The maximum thickness of these steels is 20 mm.

The mechanical properties of the high strength steels for cold forming according to EN 10149-2 (thermomechanically rolled steels) are shown in Table 12.1. The chemical composition of these steels is characterised by low carbon contents and reduced sulphur levels which are the main reasons for the improved bendability. To achieve the aimed strength levels micro-alloying elements are also often used (e.g. Nb, V, Ti).

12.2.2 Pressure vessel steels

Pressure vessel steels are generally manufactured in the same way and with similar chemical compositions as the corresponding structural steels. The main difference is the high safety requirements of the pressure vessel steels that have led to requirements of more comprehensive testing and documentation. Pressure vessel steels are standardised according to EN10028. The normalised condition is the most common even if the thermomechanically rolled and the quenched and tempered conditions are also used.

12.2.3 Abrasive resistant steels

Quenched abrasive resistant steels are in many ways similar to the most high strength structural steels, but are normally delivered only with hardness guarantee, which is the best way to guarantee a certain resistance against wear. Table 12.2 gives an example of wear plates with guaranteed Brinell-hardness and typical chemical compositions for 20 mm plate thickness. The alloy content increases with increasing plate thickness to get a uniform high hardness through the plate.

Wear plates with a hardness of up to 450 HB can be used as simple structural steels in many applications. Harder wear plates are mainly used for plain wear applications.

12.2.4 MIG welding

MIG welding is the most common welding process for structural steels. There is a wide range of both solid and cored wires that can be used. For welded joints it is important to avoid defects and to get a sufficient good toughness and strength. Welding should be performed to fulfil all the requirements of the application at use.

The properties and the quality of welds are particularly influenced by the welding condition. Thus, the following factors should be taken into consideration:

- Joint design.
- Hydrogen induced cracking.
- Toughness and hardness of the heat affected zone (HAZ).
- Static strength of the welded joint.
- Fatigue strength of the welded joint.
- Solidification cracking.
- Lamellar tearing.
- Corrosion.

Weld defects are discussed in detail in Chapter 9. The focus in this chapter will be on the first four items.

Joint design

Many different types of joints can be used for structural steels. The joint design that is most suitable depends on plate thickness, welding process, accessibility, welding position and quality requirements. If the plate thickness is larger than the weld penetration the joint has to be bevelled. In Table 12.3 examples of joint types for structural steels are presented. Recommendations for choice of joint design are given in ISO 9692.

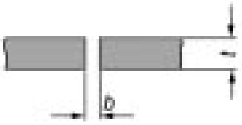
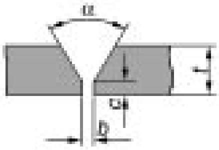
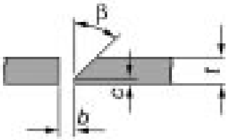
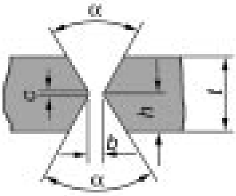
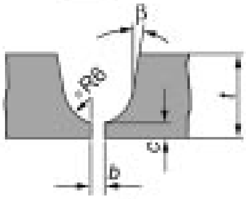
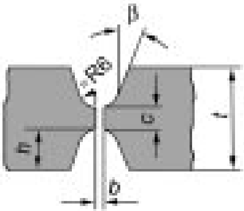
For fillet welds the edges and surfaces to be joined should be in as close contact as possible since any gap may increase the risk of cracking. Unless otherwise specified, the gap should not exceed 3 mm. Welding of holes or slots should, if possible, be avoided owing to the risk of cracking.

Table 12.2 Example of quenched abrasive resistant steels with typical chemical composition for 20 mm plate thickness

Steel	Hardness	C	Si	Mn	P	S	Cr	Ni	Mo	B	CE[1]	CET[2]
HARDOX 400	370–430 HB	0.12	0.5	1.4	0.01	0.002	–	–	–	0.002	0.37	0.26
HARDOX 450	425–475 HB	0.19	0.5	1.4	0.01	0.002	0.25	–	–	0.002	0.48	0.35
HARDOX 500	470–530 HB	0.26	0.25	1.0	0.01	0.002	0.9	–	–	0.002	0.62	0.41
HARDOX 600	570–640 HB	0.41	0.2	0.5	0.01	0.002	0.3	2	0.2	0.002	0.73	0.55

[1] CE = C + Mn/6 + (Cr+Mo+V)/5 + (Cu+Ni)/15
[2] CET = C + (Mn+Mo)/10 + (Cr+Cu)/20 + Ni/40

Table 12.3 Example of suitable joint types for structural steels. t = plate thickness, α, β = joint angle in α°, b = joint gap, c = bevelled edge. Cross-sections from ISO 9692

Joint type	Geometry, cross-section	t (mm)	α, β (α°)	b (mm)	c (mm)	Comments
I-joint		2–4 4–8	– –	1–4 2–4	– –	Single-sided welding Double-sided welding
V-joint		4–30	40° ≤ α ≤ 60°	1–4	1–3	Single- or double-sided welding
Half V-joint		3–30	35° ≤ β ≤ 60°	2–4	1–2	
Double V-joint		> 10	40° ≤ α ≤ 60°	1–3	1–2	$h = t/2$
U-joint		> 20	8° ≤ β ≤ 12°	1–4	1–3	
Double U-joint		> 40	8° ≤ β ≤ 12°	1–4	1–3	$h \approx (t - c)/2$

To reduce the stresses and distortions in a welded structure the following should be considered:

1. Avoid weld starts/stops in highly stressed areas such as corners and other sharp geometric transitions.
2. Start welding in the least flexible positions and weld towards free ends.
3. Employ balanced welding. Double preparations are better than single preparations.
4. Accuracy of preparation and fit-up.
5. Minimise the cross-sectional area of the joint. Decreased joint angles reduce the deformations.

The most common methods for joint preparation are milling and thermal cutting (gas, plasma or laser cutting). When cutting, a thin oxide layer is formed on the joint surface. The layer should be removed before welding. It is also important that oil, grease, rust, moisture, etc., are removed before welding as they can lead to weld defects such as lack of fusion, pores, solidification and hydrogen cracking.

Hydrogen induced cracking

Hydrogen cracking is one of the main problems that have to be considered when welding steel structures. Hydrogen cracking is also called cold cracking or delayed cracking and occurs at temperatures below 200ºC. Crack formation is often delayed and can appear a few days after welding. A common requirement is that inspection should not be performed before at the earliest 16 hours after welding.

For cracking to occur, three simultaneous conditions are necessary:

1. Presence of hydrogen.
2. A sensitive microstructure (usually martensite), high carbon equivalent.
3. High tensile stresses.

Hydrogen

Hydrogen is always present during welding. The most common sources are:

1. Moisture in the fluxes of cored wires.
2. Hydrogen from the atmosphere.
3. Condensation, frost or rust in the joint.
4. Oil, grease, paint, dirt, etc. in the joint or at the wire.

The hydrogen content in the plate is often low. If the welding hygiene is good the main hydrogen source is the filler material. The choice of welding process and filler material strongly influence the hydrogen content in the weld metal.

Table 12.4 Typical hydrogen contents in different types of filler materials

Welding process	Filler material	Typical hydrogen content ($\text{ml } H_2/100\,\text{g}$ weld metal)[1]
MAG	Solid wire	1–4
MAG with cored wire	Basic cored wire	2–8
MAG with cored wire	Rutile cored wire	3–15
MAG with cored wire	Metal cored wire	2–10
MMA	Basic electrode	3–10
MMA	Rutile electrode	15–35
SAW	Basic flux	3–10
SAW	Other types of flux	5–15

[1] 1 ml/100 g = 0.89 ppm

Typical hydrogen contents for different types of filler materials are presented in Table 12.4. The values vary between different products and manufacturers.

To minimise the hydrogen pick up the joint should be clean and dry before welding. A common hydrogen source is moisture at the plate. If a cold plate is taken into a warm workshop there is a risk that a condensation film is formed on the plate. When welding at temperatures below 0ºC the risk is also high that moisture will be added to the joint in the form of frost or ice.

Sensitive microstructure

For hydrogen cracking to occur, the microstructure has to be hard and brittle. The martensitic microstructure is particularly sensitive to hydrogen cracking. The carbon equivalent is a measure of the weldability of the material. A high carbon equivalent indicates an increased risk of hydrogen cracking. There are several different carbon equivalents. The most common are:

1. $CE = C + Mn/6 + (Cu+Ni)/15 + (Cr+Mo+V)/5$
2. $CET = C + (Mn+Mo)/10 + (Cr+Cu)/20 + Ni/40$
3. $Pcm = C + Si/30 + (Mn+Cu+Cr)/20 + Ni/60 + V/10 + 5B$

As a rule of the thumb materials or weld metals with a CE value below 0.40 are not sensitive to hydrogen cracking.

High tensile stresses

Residual stresses up to the yield strength of the weld metal are nearly always present in a welded joint. Residual stresses are the driving force for hydrogen cracking. Factors that influence the level of the residual stresses are the level of restraint, plate thickness, joint fit-up, weld geometry, weld sequence and the filler material strength.

Hydrogen cracking is often formed in areas with high stress concentrations such as in tack welds, in root passes or in the transition between weld and plate. A soft transition between weld and plate and at least 50 mm long tack welds are recommended to reduce the stresses in the welded joint. Large gaps strongly increase the stresses. Gaps larger than 3 mm should be avoided for fillet welds.

The most efficient way to avoid hydrogen cracking is to minimise the hydrogen pick up during welding, to use wires with low hydrogen content, to ensure that the joint is dry and clean before welding and to minimise the residual stress level in the joint.

In combination with the minimising of the hydrogen pick up it is efficient to let the absorbed hydrogen diffuse out of the welded joint before it has cooled down. The most common way to avoid hydrogen cracking when welding materials with high carbon equivalent is to preheat the joint before welding. Preheating decreases the risk of cracking partly because the high temperature increases the diffusion of hydrogen, and partly because the hardness and the residual stresses in the welded joint decrease.

Several different formulae and standards have been developed with the aim of predicting the need of preheating when welding in steels. Two methods for predicting the preheat temperatures are included in EN1011-2.

Toughness and hardness of the heat affected zone

During welding the base material adjacent to the fusion line experiences a temperature shock. This zone is called the heat affected zone, HAZ. The original microstructure is changed by the heat. Depending on the microstructure, the toughness and the hardness will also be changed. Closest to the fusion line in the HAZ the temperature has been high enough ($T > 1150\,^{\circ}\mathrm{C}$) to transform the steel and cause grain growth. This zone is generally hard and exhibits the lowest toughness in the welded joint.

Both the width of the heat affected zone and the grain size is strongly dependent of the heat input. Increasing heat input gives a wider HAZ with coarser grains and lower toughness. On the other hand the hardness in the HAZ decreases with increasing heat input. Due to risk of, for example, hydrogen cracking and stress corrosion cracking, restriction on the maximum hardness is often imposed by standards. In other words there is an optimum heat input interval (tolerance box) for achieving good properties in the welded joint. Too low heat input gives high hardness and too high heat input gives low toughness. For low strength steels the tolerance box is quite wide, there are normally no problems to get the desired properties in a welded joint of S235 steel. With increasing strength the tolerance box gets narrower. For the highest strength quenched and tempered steels it is very important to control the heat input to get good properties in the welded joint.

Strength of the welded joint

Generally the weld is always stronger than the base material. However for the highest strength quenched and tempered steels it can be hard to get a weld metal with matching strength to the base material. Most high strength wires on the market have yield strength of approximately 900 MPa. It is a limitation for the steels with even higher strength. Undermatching weld metals can, however, be accepted in many applications, for example if the welds are placed in low stressed areas or if only fillet welds are used. Matching strength is often only necessary when a high load-carrying capacity is needed transversely to a butt weld.

High strength steels for cold forming

Due to the low carbon and sulphur contents these high strength steels for cold forming have very good weldability. The risk for hydrogen cracking and hot cracking is very low and there is no need for preheating when these steels are welded.

12.3 Cold rolled and zinc coated sheet steels

12.3.1 Structural steels

In the same way as for hot rolled structural steels, cold rolled structural steels in thicknesses up to about 3 mm are also widely used. These cold rolled sheet steels have a minimum guaranteed yield strength and tensile strength. In many applications the corrosion resistance of the material is very important and therefore different types of zinc coated sheet steels are also used.

Cold rolled steels

This type of uncoated cold rolled sheet steels have been used for many years and are available as standardised steels according to the European Standard EN 10268. These cold rolled sheet steels in EN 10268 (H 240 LA, H 280 LA, H 320 LA, H 360 LA, H 400 LA) are used in the same type of applications as the hot rolled structural steels in EN 10025 (S235…, S275… and S355…). The cold-rolled sheet steels are especially used when the thickness tolerances have to be very tight or good surface appearance is an important factor. The chemical composition and mechanical properties of these cold rolled steels according to EN 10268 are shown in Table 12.5. Maximum thickness for these cold rolled sheet steels is normally 3 mm.

The production process at the steel mill is that after cold rolling, the steels are recrystallisation annealed and skin passed. The annealing can be performed

Table 12.5 Uncoated cold rolled structural steels according to EN 10268

Steel designation		Chemical composition							Strength		Elongation
Steel name	Number	C % max	Si % max	Mn % max	P and S % max	Al % min	Nb % max[1]	Ti % max[1]	R_{eH} N/mm^2 min–max[2]	R_m N/mm^2 min[2]	A_{80} % min[2]
H 240 LA	1.0480	0.10	0.50	0.60	0.025	0.015	0.090	0.15	240–310	340	27
H 280 LA	1.0489	0.10	0.50	0.80	0.025	0.015	0.090	0.15	280–360	370	24
H 320 LA	1.0548	0.10	0.50	1.00	0.025	0.015	0.090	0.15	320–410	400	22
H 360 LA	1.0550	0.10	0.50	1.20	0.025	0.015	0.090	0.15	360–460	430	20
H 400 LA	1.0556	0.10	0.50	1.40	0.025	0.015	0.090	0.15	400–500	460	18

[1] Vanadium may also be used. The sum of the contents of Nb, Ti and V should not exceed 0.22%

[2] Longitudinal to the rolling direction

either by batch annealing or by continuous annealing. All the steels have lean chemical compositions and often conventional carbon manganese steels are used for the steels of low strength. For steels of higher strength small amounts of micro-alloying elements are normally added (niobium or titanium). Around the world this type of high strength steel is also known as cold rolled HSLA steel (High Strength Low Alloyed). For other types of high strength steel (see Section 12.3.3).

Zinc coated sheet steels

Different types of hot-dip coated structural steels with improved corrosion resistance are also often used. The most common coating is hot-dip zinc coating with the coating designation 'Z' but other types of hot-dip coatings are also available such as, for example, hot-dip zinc-iron coating ('ZF'), hot-dip zinc-aluminium alloy coating ('ZA'), hot-dip aluminium-zinc alloy coating ('AZ') and hot-dip aluminium-silicon alloy coating ('AS'). The hot-dip coated steels conform to the European Standard EN 10326 'Continuously hot-dip coated strip and sheet of structural steels' (S220GD, S250GD, S280GD, S320GD, S350GD, S550GD). The sheets are often used in metal coated condition but the metal coated steels are in many cases afterwards coil coated at the mill by the steel producer and then used in the different applications (for example, as roll-formed steels for roofs and walls in buildings).

The chemical compositions and mechanical properties of the hot-dip coated steels according to EN 10326 are shown in Table 12.6. This table shows that these steels are available in many different strength levels. The maximum thickness for this type of hot-dip coated steels is normally 3 mm.

The cold rolled strip is recrystallisation annealed in a continuous process and in this process the coating is also applied by hot dipping the strip in a molten bath. This type of continuous process can be controlled very well so the thickness of the coating can reach the desired values.

The coating masses are specified as the minimum coating mass (g/m^2, total mass for both surfaces) for the steel, see Table 12.7 where an example is given for the hot-dip zinc coated steel.

12.3.2 Sheet steels for cold forming

Sheet steels are also often used in components with a complex geometry. To be able to press these components sheet steels with good formability are needed. For many of the components the loads are low and in fact when specifying such a sheet steel often a maximum strength is prescribed. For this type of application both uncoated cold rolled sheet steels and metal coated sheet steels (most common is zinc coating) are used. The maximum thickness for this type of steel is normally 3 mm.

Table 12.6 Hot-dip coated structural steels according to EN 10326

Steel designation		Chemical composition					Strength		Elongation
Steel name	Steel number	C % max	Si % max	Mn % max	P % max	S % max	$R_{p0.2}$ MPa min[1]	R_m MPa min[1]	A_{80} % min[1]
S220GD	1.0241	0.20	0.60	1.70	0.10	0.045	220	300	20
S250GD	1.0242	0.20	0.60	1.70	0.10	0.045	250	330	19
S280GD	1.0244	0.20	0.60	1.70	0.10	0.045	280	360	18
S320GD	1.0250	0.20	0.60	1.70	0.10	0.045	320	390	17
S350GD	1.0529	0.20	0.60	1.70	0.10	0.045	350	420	16
S550GD	1.0531	0.20	0.60	1.70	0.10	0.045	550	560	

[1] Longitudinal direction

Table 12.7 Zinc coating masses for hot-dip zinc coated steels according to EN 10326

Coating designation	Minimum zinc coating mass, g/m^2, total both surfaces	Corresponding coating thickness per surface (μm)
Z100	100	7
Z140	140	10
Z200	200	14
Z225	225	16
Z275	275	20
Z350	350	25
Z450	450	32
Z600	600	42

Cold rolled sheet steels

The steels in this group can be found in the European Standard EN 10130 'Cold rolled low carbon steel flat products for cold forming'. Typical applications for these steels are, for example, components in the automotive industry, household machines, different parts within the electronic sector.

The chemical composition and mechanical properties of these uncoated cold rolled steels according to the European Standard EN 10130 are shown in Table 12.8. In this table values which are connected to the formability properties of the steels are also given, i.e. the plastic strain ratio (r-value, a measure of drawability) and strain hardening exponent (n-value, a measure of stretchability).

After cold rolling the steels are annealed and skin passed. The annealing can be conducted either by batch annealing or by continuous annealing. The chemical compositions specified in the European Standard EN 10130 show that the steels have very lean chemical compositions with low carbon contents. For the most formable steel (DC06) often an extremely low level of carbon is used, typically approximately 0.003% (ULC steels, ultra low carbon steels). The carbon and nitrogen are in this case tied up by the addition of titanium or niobium giving very good formability and strain ageing properties.

Zinc coated steels

Metal coated sheet steels for pressing and stamping with improved corrosion resistance are also often used. The most common type of metal coating is hot-dip zinc coating ('Z') but also other types of hot-dip coatings are available as, for example, hot-dip zinc-iron coating ('ZF'), hot-dip zinc-aluminium alloy coating ('ZA'), hot-dip aluminium-zinc alloy coating ('AZ') and hot-dip aluminium-silicon alloy coating ('AS'). The hot-dip coated steels conform to the European Standard EN 10327 'Continuously hot-dip coated strip and sheet of low carbon

Table 12.8 Uncoated cold rolled steels for cold forming according to EN 10130

Steel designation		Chemical composition					Strength		Elongation	Formability	
Steel name	Steel number	C % max	Mn % max	P % max	S % max	Ti % max[1]	$R_{p0.2}$ N/mm^2 max	R_m N/mm^2 min–max	A_{80} % min	r_{90}[2] min	n_{90}[2] min
DC 01	1.0330	0.12	0.60	0.045	0.045		280	270–410	28		
DC 03	1.0347	0.10	0.45	0.035	0.035		240	270–370	34	1.3	
DC 04	1.0338	0.08	0.40	0.030	0.030		210	270–350	38	1.6	0.18
DC 05	1.0312	0.06	0.35	0.025	0.025		180	270–330	40	1.9	0.20
DC 06	1.0873	0.02	0.25	0.020	0.020	0.3	180	270–350	38	1.8	0.22

[1] Titanium may be replaced by niobium. Carbon and nitrogen should be completely bound

[2] r_{90} and n_{90} refer to transverse direction. The values for DC 06 refer to the average value of the different directions (0, 90 and 45)

steels for cold forming' (DX51D, DX52D, DX53D, DX54D, DX56D and DX57D). Typical applications for these steels are components in ventilation equipment and fan installations, stamped parts in cars and such things.

As an example the chemical compositions, mechanical properties and formability values (r- and n-values) of the hot-dip zinc coated steels (Z) according to the European Standard EN 10327 are shown in Table 12.9. The different steel grades are classified in accordance with their increasing suitability for cold forming. For example, DX51D is normally used in simple bending operations and DX57D is used in operations which demands extremly good deep drawing or stretching properties.

The starting material at the steel mill is a cold rolled strip which is recrystallisation annealed in a continuous process and in this process the coating is also applied by hot dipping the strip in a molten bath. This process can be controlled very well so the thickness of the coating can be kept within the specified values. In the same way as for the uncoated steels for cold forming these steels have very lean chemical compositions with low carbon contents. These metal coated sheet steels for cold forming are available in a wide range of coating thicknesses, e.g. from 7 μm to 42 μm (Z100 to Z600) for the hot-dip zinc coated steels.

12.3.3 High strength sheet steels for cold forming

There are also many different types of high strength sheet steels with good formability available. With high strength sheet steels it is possible to reduce the weight of a construction or to increase the performance of the product. In the automotive industry high strength steels are often used to save weight or to increase the safety of the car. High strength steels are available both as cold rolled uncoated steels and as zinc coated steels. There are sometimes different minimum yield strength values given for the definition of high strength steels. In the automotive industry a minimum yield strength of 210 N/mm^2 is often used to define a high strength steel and in some of the European Standards steels with a minimum yield strength of 180 are also denominated high strength steels.

Cold rolled high strength steels (uncoated)

Owing to the great interest for high strength steels, many different types of high strength steels have been developed. As an example the following different types of high strength steels can be mentioned (the most common designation used in parenthesis):

Interstitial free (Y)
Bake hardened (B)
Rephosphorised (P)

Table 12.9 Hot-dip zinc coated steels for cold forming according to EN 10327

Steel designation		Chemical composition					Strength		Elongation	Formability	
Steel name	Steel number	C % max	Si % max	Mn % max	P % max	S % max	R_e N/mm^2 min–max[1]	R_m N/mm^2 min–max[1]	A_{80} % min	r_{90} min	n_{90} min
DX51D	1.0226	0.12	0.50	0.60	0.10	0.045	–	270–500	22	–	–
DX52D	1.0350	0.12	0.50	0.60	0.10	0.045	140–300	270–420	26	–	–
DX53D	1.0355	0.12	0.50	0.60	0.10	0.045	140–260	270–380	30	–	–
DX54D	1.0306	0.12	0.50	0.60	0.10	0.045	120–220	260–350	36	1.6	0.18
DX56D	1.0322	0.12	0.50	0.60	0.10	0.045	120–180	260–350	39	1.9	0.21
DX57D	1.0853	0.12	0.50	0.60	0.10	0.045	120–170	260–350	41	2.1	0.22

[1] Transverse test pieces

Low alloy or micro-alloyed (LA or HSLA)
Dual-phase steel (DP)
Complex phase steel (CP)
TRIP steels (TRIP)
Martensitic steels (M)

The different types of high strength steel have very different strength and formability properties. For example, the interstitial free, bake hardened and rephosphorised steels, with quite low strength levels, have a minimum yield strength range of about 180–260 N/mm^2 in combination with very good formability and there are martensitic high strength steels with a yield strength of as high as 1200 N/mm^2 which is intended for usage only in components where the demands on the forming properties are very moderate. The dual-phase steels, complex phase steels and TRIP steels, with strengths in the medium range (minimum yield strength of about 300–800 N/mm^2), exhibit a very good combination of strength and formability. The reason for this is a better strain hardening capacity for these steels in comparison to the other high strength steels and this is due to another type of microstructure for these steels. These steels are multiphase steels and the microstructure of these steels consists of several phases (for example, ferrite, martensite, bainite, retained austenite) giving them enhanced mechanical properties. The most common type of these steels today is the dual-phase steels with a microstructure of ferrite and martensite.

Regarding the chemical compositions of the high strength steels, the carbon contents are quite low for the steels of rather low strength (e.g. maximum about 0.10% for the interstitial free, bake hardened, rephosphorised and micro-alloyed steels). Typical carbon contents for the dual-phase and complex phase steels are in the range of 0.10–0.17%. To produce TRIP steels and some of the martensitic steels more alloying contents are needed and the carbon content for these steels is often in the range of 0.20–0.30%.

It should be mentioned that within each of the different steel groups mentioned above there are many steel grades with different strength levels so the total number of available high strength steel grades is very high. Up to now no European Standards existed for these cold rolled high strength steels but work is going on in this area so within some years such standards will probably be available.

Zinc coated high strength steels

Metal coated high strength steels with improved corrosion resistance are also available. Especially in the automotive industry large tonnages of such steels are used and the most common type of coated steels here are hot-dip zinc coated steels and electrolytic galvanised steels.

The different types of high strength steels are the same as those used for the cold rolled high strength steels. The metal coated high strength steels of moderate strengths (interstitial free, bake hardened, rephosphorised and low-alloy steels) are covered by the European Standard EN 10292, 'Continuously hot-dip coated strip and sheet of steels with higher strength for cold forming'. The different coatings included in this standard are hot-dip zinc coated (Z), hot-dip zinc-iron coating (ZF), hot-dip zinc-aluminium alloy coating (ZA), hot-dip aluminium-zinc alloy coating (AZ) and hot-dip aluminium-silicon alloy coating (AS). The chemical compositions and mechanical properties for steels according to EN 10292 are shown in Tables 12.10 and 12.11.

For the coated steels of high strength (dual phase, TRIP and complex phase steels) and very high strength steels (martensitic) there are no European Standards available yet but work is in progress in this area so within some years such standards will probably be available.

These metal coated high strength sheet steels for cold forming are available in a wide range of coating thicknesses, for example, from 7 μm to 20 μm (Z100 to Z275) for the hot-dip zinc coated steels. For the electrolytic galvanised steels it is also possible to get sheets with a coating thickness $< 7\ \mu$m.

12.3.4 MIG welding

MIG welding is the most common fusion welding method for sheet steels. This welding method can be used down to a sheet thickness of approximately 0.7 mm (for sheet thicknesses <0.7 mm TIG welding is often used). There is a wide range of solid wires that can be used for MIG welding of sheet steels. The diameter of the wires used is normally 0.6 mm or 0.8 mm. Cored wires can also be used even if the use of cored wires is still not very common for sheet steels.

Various types of shielding gases can be used for MIG welding of sheet steels, for example mixed gases (Ar/CO_2) and pure CO_2. A gas mixture of Ar and CO_2 (5–25%) is the most common shielding gas and it offers very good welding properties. Pure CO_2 as shielding gas is cheaper than the mixed gases but pure CO_2 causes more spatter and makes greater demands on more accurate welding parameter settings to ensure a good welding result.

More information about MIG welding of sheet steels can be found in reference 4.

Joint design

Many different types of joints can be used when sheet steels are MIG welded, for example lap joints, fillet joints and butt joints (see Fig. 12.2). Square butt joints without any special joint preparations are normally used for butt welding. Shearing, punching or laser cutting can be used for preparing the sheets. The requirements on the edges are not very strict and the gap may vary somewhat

Table 12.10 Chemical composition of hot-dip coated high strength steels according to EN10292

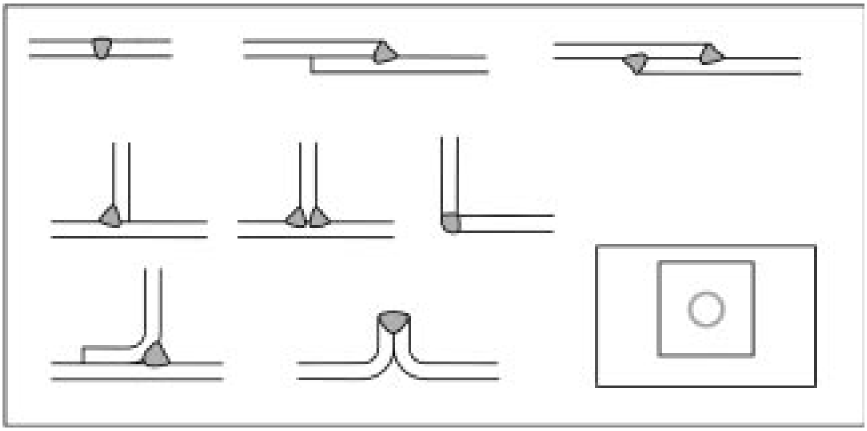
Steel designation		Chemical composition							
Steel name[1]	Steel number	C % max	Si % max	Mn % max	P % max	S %	Al % min	Ti % max[2]	Nb % max[2]
H180YD	1.0921	0.01	0.10	0.70	0.06	0.025	0.02	0.12	–
H180BD	1.0354	0.04	0.50	0.70	0.06	0.025	0.02	–	–
H220YD	1.0923	0.01	0.10	0.90	0.08	0.025	0.02	0.12	–
H220PD	1.0358	0.06	0.50	0.70	0.08	0.025	0.02	–	–
H220BD	1.0353	0.06	0.10	0.70	0.08	0.025	0.02	–	–
H260YD	1.0926	0.01	0.50	1.60	0.10	0.025	0.02	0.12	–
H260PD	1.0431	0.11	0.50	0.70	0.10	0.025	0.02	–	–
H260BD	1.0433	0.11	0.50	0.70	0.10	0.025	0.02	–	–
H260LAD	1.0929	0.11	0.50	0.60	0.025	0.025	0.015	0.15	0.09
H300PD	1.0443	0.11	0.50	0.70	0.12	0.025	0.02	–	–
H300BD	1.0445	0.11	0.50	0.70	0.025	0.025	0.015	–	0.09
H300LAD	1.0932	0.11	0.50	1.00	0.025	0.025	0.015	0.15	0.09
H340LAD	1.0933	0.11	0.50	1.00	0.025	0.025	0.015	0.15	0.09
H380LAD	1.0934	0.11	0.50	1.40	0.025	0.025	0.015	0.15	0.09
H420LAD	1.0935	0.11	0.50	1.40	0.025	0.025	0.015	0.15	0.09

[1] **Y** = interstitial free. **B** = bake hardened. **P** = rephosphorised. **LA** = low alloy (micro-alloyed)
[2] V and B may also be used. The sum of the contents of Ti. Nb and V should not exceed 0.22%

Table 12.11 Mechanical properties of hot-dip coated high strength steels according to EN10292

Steel designation		Strength		Elongation	Formability	
Steel name	Steel number	$R_{p0.2}$ N/mm^2 min–max[1]	R_m N/mm^2 min–max[1]	A_{80} % min	r_{90} min	n_{90} min
H180YD	1.0921	180–240	340–400	34	1.7	0.18
H180BD	1.0354	180–240	300–360	34	1.5	0.16
H220YD	1.0923	220–280	340–410	32	1.5	0.17
H220PD	1.0358	220–280	340–400	32	1.3	0.15
H220BD	1.0353	220–280	340–400	32	1.2	0.15
H260YD	1.0926	260–320	380–440	30	1.4	0.16
H260PD	1.0431	260–320	380–440	28	–	–
H260BD	1.0433	260–320	360–440	28	–	–
H260LAD	1.0929	260–320	350–430	26	–	–
H300PD	1.0443	300–360	400–480	26	–	–
H300BD	1.0445	300–360	400–480	26	–	–
H300LAD	1.0932	300–380	380–480	23	–	–
H340LAD	1.0933	340–420	410–510	21	–	–
H380LAD	1.0934	380–480	440–560	19	–	–
H420LAD	1.0935	420–520	470–590	17	–	–

[1] Transverse test pieces



12.2 Examples of different joint types used for MIG welding of cold rolled and zinc coated sheet steel.

and the cut surface need not be perfectly square. For the fillet joints and lap joints (the most common joint type) the demands on the edges are also moderate.

MIG welding of cold rolled sheet steels

Welding of sheet steels makes strict demands on the welding parameters. In addition to the common operator-related welding defects it is also important when welding sheet steels to avoid burning through and deformation of the sheets. The joint geometry tolerances are also tight. In MIG welding of sheet steel several parameters (e.g. welding gun angle, stick-out, welding speed) are more important than when welding thicker material. Forehand angle is normally employed for welding sheet steel. The forehand angle offers benefits such as higher productivity, more favourable geometry between weld metal and base metal and less risk of burning through. There is also little risk of lack of fusion.

Cold rolled sheet steel is normally very clean and the problem with porosity due to the material itself is very rare. Before delivery the sheet steel is normally coated with a thin oil film in order to avoid corrosion damage. This oil film is so thin that it does not give rise to porosity problems in combination with MIG welding.

Other types of defects which can sometimes occur for thicker plates i.e. cold cracks (hydrogen cracks), hot cracks (solidification cracks) and lamellar tearing are not a problem when MIG welding cold rolled sheet steels. This is mainly due to factors such as low impurity levels, low amounts of alloying elements and low cooling rates for these thin sheet steels.

There are solid wires of various strength levels available for MIG welding of cold rolled sheet steels, both for mild steels and high strength steels. For the steels of very high strength (ultimate tensile strength $> 1000\,\text{N/mm}^2$) there are no matching filler metals available. For these steels undermatching wires are used.

The static strength of butt welds with the load across the weld is at least as high as the base material for mild steels and high strength steels of medium strength (bake hardened, rephosphorised, HSLA, dual phase steels). During tensile testing the failure takes place to one side of the weld in the base metal. For steels of even higher strength (for example, martensitic steels) the strength increases with increasing strength of the base metal, although the strength of the weld in this case is somewhat lower than the base metal. The reason is that the heat of welding causes soft zones in the HAZ. Failure during tensile testing takes place in these zones. Lap welds have normally somewhat lower strength than butt welds. The reason is that a bending moment occurs for the lap weld, which adds an extra stress locally in the weld.

In general it is often positive for the static strength of a weld to use a low heat input. For thick plates a reduction of the heat input can be reached by welding with an increased number of passes. For thin sheets there is a limited possibility to change the heat input. The reason is that sheet steels are normally welded with only one bead and the geometry requirement of the weld determines the heat input needed.

MIG welding of zinc coated sheet steels

Zinc coated sheet steels are somewhat more difficult to weld than cold rolled sheet steels. Special measures must therefore be taken in certain cases in order to get a good welding result. The basic reason for making zinc coated steels more difficult to weld is that the zinc coating quickly gasifies during welding. The boiling temperature of zinc is 907 °C, which is much lower than the melting temperature of steel, which is at about 1500 °C. This affects the stability of the arc and it may sometimes be difficult to weld in the normal way. In addition to this spatter and porosity of the weld may occur. The penetration can also be somewhat reduced since energy is also needed for burning the zinc. As always exhaust equipment should be used when zinc coated sheet steels are MIG welded.

The type of joint is very important for the welding result. Butt joints and corner joints seldom cause any problems but lap joints and fillet joints require more attention. The reason is that the zinc vapour easily is trapped in the weld metal for this type of joint. The zinc coating is burnt away entirely during the welding process. In certain cases the coating on the reverse side of a fillet weld or lap weld may more or less disappear and the corrosion resistance of the sheet will be impaired. Whether or not the zinc coating on the reverse side can be retained in such joints depends on several factors such as sheet thickness, heat input, gun angles, coating thickness, etc.

The difficulties during MIG welding of zinc coated sheets increase with increased amounts of zinc. Sheet steel with a thick zinc layer is therefore more difficult to weld than sheet steel with a thin layer. The best solution from the welding aspect is to grind away the zinc coating locally. In order to retain good corrosion resistance after welding, regardless of whether or not the coating has been removed locally, some form of anti-corrosion treatment is needed, such as painting with a zinc-rich paint. If the zinc coating cannot be ground away, one or several of the following measures are recommended when joints of difficult geometry are to be welded:

- Use as thin a coating as possible.
- Lower the travel speed.
- If possible use a narrow gap between the sheets.
- Spray the sheets with anti-spatter oil before welding.
- Use a special flux-cored wire intended for MIG welding of zinc coated sheet steels.

12.4 Bibliography

1. EN 1011-2, *Welding – Recommendations for welding of metallic materials – Part 2: Arc welding of ferritic steels*.
2. T B Larsson and T Berglund (1992) *Handbook on Welding of Oxelösund Steels*.
3. N Bailey, F R Coe, T G Gooch, P H M Hart, N Jenkins and R J Pargeter, *Welding Steels Without Hydrogen Cracking*. ISBN 1855730146.
4. *Sheet Steel Joining Handbook*. SSAB Tunnplåt AB, Sweden, 2005.

13

MIG welding of stainless steel

G LINDÉN, Air Liquide Gas AB, Sweden

13.1 Introduction

Stainless steels have a chromium content of more than 12%. A thin, tenacious oxide layer is formed on the surface, which prevents the material from further corrosion and oxidation. Depending on the corrosive gaseous or liquid media, other alloying elements are also added to reinforce the resistance against corrosion. The most common alloying elements besides chromium are nickel and molybdenum. For weldable stainless steels the carbon content is normally below 0.1%.

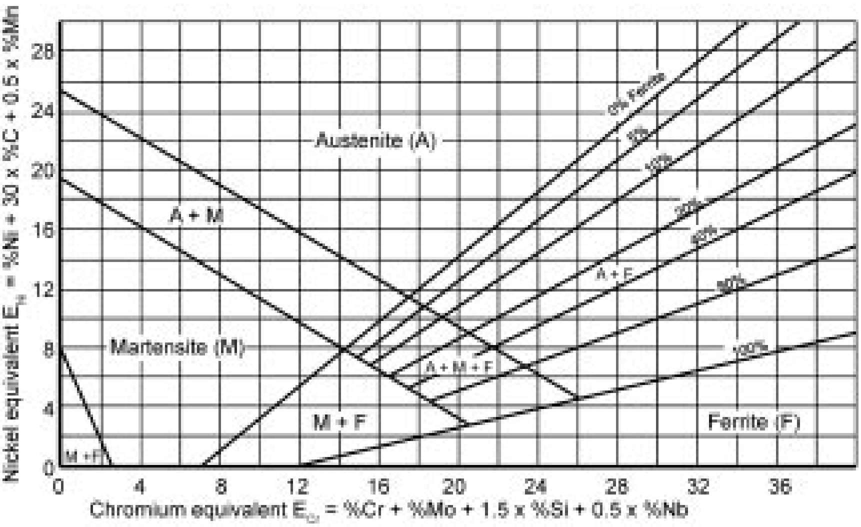
The same mechanism as for corrosion also improves the oxidation properties of these steels compared to plain carbon steels.

The unalloyed steel has a ferritic microstructure at room temperature. Alloying elements used in stainless steels modify the microstructure considerably. The main microstructures are:

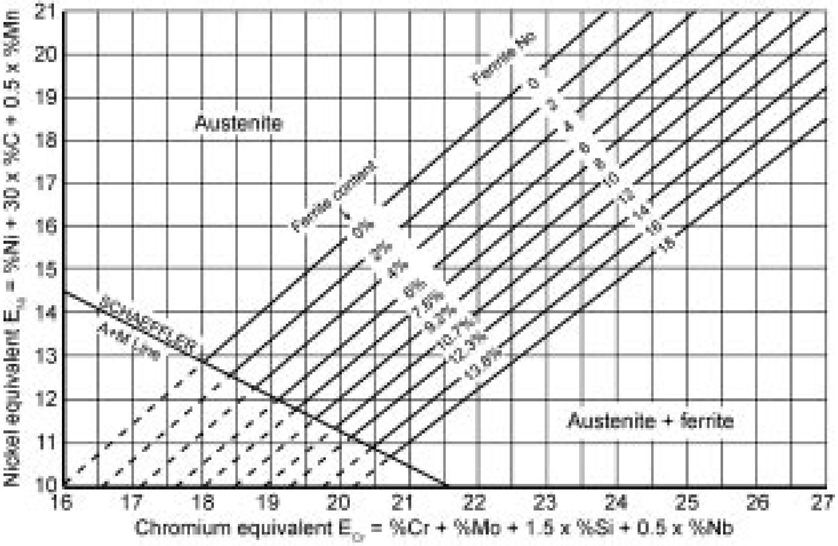
- Austenite.
- Ferrite.
- Ferrite/austenite mixtures.
- Martensite (normally not used for welding applications).
- Ferrite/martensite.

The Shaeffler diagram in Fig. 13.1 gives an overview of the microstructures that appear in welds depending on the alloying elements at room temperature. These elements are divided into two groups, the austenite forming elements and the ferrite forming elements. The first ones favour the formation of an austenitic microstructure and their effect is summarised in the nickel equivalent with different coefficients. The strongest effect is from carbon. The ferrite forming elements are summarised in the chromium equivalent. Modern stainless steels also contain nitrogen as an alloying element. Special diagrams like the DeLong diagram in Fig. 13.2 also includes nitrogen, which is a strong austenite forming element similar to carbon.

The microstructure in the stainless steel weld material is found by calculating



13.1 Shaeffler diagram.



13.2 DeLong diagram.

the nickel and chromium equivalents and then find the corresponding point in the diagram.

13.2 Austenitic steels

Austenitic stainless steels are alloyed with chromium, nickel and sometimes molybdenum. This type of steel has a wide use from household appliances to severe environments in the chemical industry. To achieve a fully austenitic microstructure the steel is often rapidly cooled from 1050–1100 °C. The carbon content is normally low < 0.05% or < 0.03% for ELC steels (extra low carbon). The risk of chromium carbide formation in the grain boundaries during the reheating in welding is minimised by the low carbon content. In other austenitic stainless steels the carbon content may be somewhat higher but the steel is then stabilised with titanium or niobium. These elements form stable carbides, more stable than chromium carbides, and take care of the carbon and chromium carbide precipitation is prevented.

Austenitic steels are not hardenable by heat treatment since there is only one phase and no phase transformation possible to use. The yield stresses are fairly low in the annealed and rapid cooled state. Austenite is also non-magnetic.

Cold deformation is the most efficient hardening mechanism. The austenite transforms to martensite during cold rolling or during the forming process of the annealed and rapidly quenched material.

13.2.1 MIG welding of austenitic steel

MIG welding of austenitic stainless steels is used frequently. To achieve the right microstructure a filler material of the same composition as the base material is normally used.

The same types of joint as for plain carbon steels are used. The thermal expansion is about 50% higher and the thermal conductivity 40% lower than plain carbon steels. Thus there will be considerable deformation around the weld and this must be taken into account during welding. Low heat input and careful planning of the sequence of the welds are important to minimise the deformation. On the other hand, too low a heat input gives a risk of lack of fusion.

Hot cracking may occur in fully austenitic welds. Elements such as sulphur and phosphorus are not easily dissolved in austenite and can segregate to the grain boundaries and give hot cracking when the weld solidifies. Small amounts of 3–8% of ferrite prevent the hot cracking. The ferrite can dissolve the critical impurity elements and no segregation of harmful phases occurs. The ferrite content should be minimised because it forms a continuous network at about 10% and selective corrosion can occur. There is also a risk for the formation of a brittle sigma phase when the construction is used at operating temperatures in the range 550–900 °C. In some cases ferrite-free welds are required. Special filler materials with very low impurity contents and increased manganese content are available today. Heat treatment at 1050–1100 °C followed by rapid cooling gives the right microstructure but is not possible from practical reasons.

Another major problem for austenitic steels is the risk of intercrystalline corrosion in severe environments. If chromium carbides are precipitated in the HAZ during welding there will be a depletion of chromium near the grain boundaries depending on the different diffusion rate of carbon and chromium. Carbon atoms diffuse more rapidly. The depleted zones corrode due to the low chromium content and there will be intergranular cracks.

By decreasing the holding time in the critical temperature range about 500–850 °C the risk of intercrystalline corrosion is decreased. The heat input must be carefully controlled. Another possibility is the selection of a base material with extra low carbon content (ELC) and low carbon filler materials. The shielding gas for solid wires should be either argon with low amount of carbon dioxide (normally 2%) or argon mixed with oxygen. Very small amounts of carbon will then be added to the material. Stabilised austenitic steels contain titanium or niobium, that forms carbide more easily than chromium and therefore no carbon is available to form chromium carbides.

Austenitic stainless steels are sometimes welded together with either other stainless steels or with plain carbon steels or low-alloyed steels. The Shaeffler diagram (Fig. 13.1) can be useful to find out the microstructure of the weld. The chemical composition of the weld will be a dilution of filler metal composition with the base materials. The microstructure of the weld must be austenite with some ferrite. To achieve this it is often necessary to use solid wires with higher amounts of nickel and chromium than normally used in welding of only austenitic steels.

The oxidised surface near to the weld caused by the high temperature and sometimes insufficient gas shielding during welding must be carefully removed if the corrosion resistance is to be good. During oxidation there is a depletion of alloying elements and pitting corrosion may occur.

Austenite is also sensitive to penetration of zinc, copper and aluminium at high temperatures. These metals have low surface energy and penetrate the grain boundaries of the austenite. The grain size of the austenite is also often big. The penetration is promoted by tensile stresses in the metal. The penetration will cause cracking. Zinc may emanate from galvanised steel that is to be welded to the stainless steel. Zinc may also come from paints for corrosion protection that are used for joints between stainless and plain steel. Brushes may also contain impurities of copper or aluminium.

13.3 Ferritic steels

The ferritic steels are used in similar applications to austenitic steels but have special advantages in certain environments. Ferritic steels are less sensitive to stress corrosion cracking compared to austenitic steels.

The main alloying element in ferritic stainless steels is chromium. Carbon content is normally less than 0.1%. Ferritic steels are magnetic and non-hardenable.

13.3.1 MIG welding of ferritic steels

Welding of ferritic steels is more difficult than for austenitic steels. During welding there will be a significant increase in grain size and precipitation in the grain boundaries of carbides. Ferritic steels are generally much more brittle at big grain size than austenitic steels. Thus the welds will be embrittled and the corrosion resistance will be lowered. A subsequent heat treatment is often necessary.

By decreasing the amount of carbon and nitrogen in the steels or by stabilising the steels with titanium to form carbide, the weldability of these steels has been improved. The filler materials used are either of the same composition as the base materials or an austenitic steel, which gives the weld a higher ductility.

13.4 Ferritic-austenitic steels

The ferritic-austenitic steels are also called duplex stainless steels. The microstructure consists of about the same amount of ferrite and austenite. These steels combine good mechanical properties with excellent corrosion behaviour. An important application is in the offshore industry. Other applications are in the chemical and petrochemical industry and the pulp and paper industry. A high strength means that constructions can be made lighter.

These steels are alloyed with high amounts of chromium, nickel and molybdenum and a low carbon content of less than 0.03%. Nitrogen is an important alloying element, which is present in concentrations up to 0.4%. Nitrogen has the advantage compared to the other alloying elements that it diffuses very rapidly since the atoms are smaller and alloyed as interstitials in the microstructure. The weld pool solidifies primarily as a fully ferritic structure. The austenite is formed at lower temperatures as a precipitation from the ferrite grain boundaries. Owing to the presence of nitrogen this is accelerated compared to earlier types of duplex steels without nitrogen.

The deformation during welding is small compared to austenitic steels.

13.4.1 MIG welding of ferritic-austenitic steels

The filler material used is of similar composition as the base material but with somewhat higher nickel content to assist the austenite formation and produce a similar microstructure as in the base material. This ensures the optimum combination of mechanical properties and corrosion resistance. Since nitrogen disappears in the weld pool during welding; to a certain degree a shielding gas with nitrogen addition can be used to compensate for the loss.

It is important to control the heat input carefully. As an example for the low-alloyed types the heat input should be between 0.5 and 2.5 kJ/mm and there is also a limitation on interpass temperature lower than 250 °C. Too high a heat input and high temperature between weld passes can produce a sigma phase, which gives lower corrosion resistance and increased brittleness. Too low a heat input, on the other hand, can lead to rapid cooling giving too high a ferrite content in the microstructure. Precipitation of chromium nitrides may also appear that decreases the corrosion resistance.

13.5 Ferritic-martensitic steels

Fully ferritic steels often have the disadvantage of excessive grain growth in the HAZ during welding. By controlling the composition and production of steels with about 11% Cr and minor additions of Ni, Mn and Si it is possible to obtain a duplex ferritic-martensitic structure. Owing to the two-phase microstructure of ferrite and tempered martensite the grain size is small, which gives good mechanical properties. Negligible embrittlement is found after long exposures at temperatures of 450–550 °C.

13.5.1 MIG welding of ferritic-martensitic steels

Both short arc and spray arc welding with solid wires is possible. Also flux-cored electrodes are used. The heat input per weld pass should be limited to 1.0 kJ/mm in order to control the grain growth in the HAZ. Filler wires of the austenitic stainless steel types are recommended and the shielding gases are those recommended for these types of filler materials, i.e. argon or argon–helium mixtures with minor addition of carbon dioxide or oxygen.

13.6 Conclusion

It is a general rule to keep the weld area of the stainless steel free from all types of impurities before welding. Oil, paint and dust, etc., must be removed otherwise they will lead to weld discontinuities (especially dust from carbon steel can reduce the corrosion resistance of the material). Stainless steel welding is very often done in a special workshop separated from the welding in plain steels.

To get acceptable corrosion resistance of the material after welding the oxides must be removed. Oxides may lead to local corrosion attacks in critical environments. The oxides can be removed mechanically by grinding, brushing and similar techniques or by chemical pickling in baths or by special pastes. All the tools used must be dedicated to stainless steel only, for example stainless steel brushes. Blasting must be done using blasting material free from impurities of plain steel particles. Special care must also be taken in the handling of stainless steel to avoid direct contact with plain steel.

13.7 Bibliography

Pettersson, C-O. (2003) in Weman, K. (ed.) *Welding Processes Handbook*. Cambridge, Woodhead, pp. 138–47.

14

MIG welding of aluminium and aluminium alloys

G LINDÉN, Air Liquide Gas AB, Sweden

14.1 Introduction

Aluminium and aluminium alloys are frequently used in welded constructions. The low density means that the constructions are lightweight. The thin and tenacious layer of aluminium oxide on the surface gives good corrosion behaviour in many environments. The oxide layer is healed in air if it is damaged. Most aluminium alloys are easily formed by rolling, forging and extrusion. Extruded profiles of sophisticated shapes can be manufactured and give unique possibilities for the designers. Casting is also often used.

14.2 The properties of aluminium and its alloys

Aluminium has a face-centred cubic structure of similar type to the austenitic stainless steel. This means that the toughness does not drastically decrease when the temperature is reduced. The microstructure of solid aluminium and its alloys does not change on heating and cooling.

The heat and electrical conductivities are high. The deformations during welding are also high depending on the high coefficient of thermal expansion. Aluminium is also non-magnetic.

Unalloyed aluminium is very soft. One application is electrical contacts with high demands on electrical conductivity. Alloying elements increase the strength by solid solution hardening or by precipitation hardening. Magnesium (Mg), manganese (Mn), copper (Cu) and zinc (Zn) are frequently used. Silicon (Si) may be added deliberately but is also present as an impurity together with iron (Fe) from the ore.

Solid solution hardening means that the alloying element is present as substitutional elements in the face-centred cubic microstructure. Mg and Mn have this effect. These alloys are often called non-hardenable and the only way to increase their strength is by cold deformation usually cold rolling.

Precipitation hardening means that very small particles are precipitated in the microstructure after heat treatment. The material is heated to a temperature where the alloying elements are completely dissolved in the material. The fast cooling is followed by an ageing treatment at room temperature, (naturally aged) for some alloys. Some other alloys have to be treated at a somewhat higher temperature (artificially aged) to reach the maximum strength. During this treatment small particles are nucleated in the supersaturated phase. Small particles are effective obstacles to dislocation movements and therefore increase the strength considerably, normally much more than solid solution strengthening. A disadvantage is that too much heat coarsens the particles and the effect is reduced (overageing). Typical particles in precipitation hardening are Al_2Cu, Mg_2Si and Zn_2Mg. The alloys are called heat-treatable if the precipitation hardening mechanism is used to get the high strength.

Some properties are important for the welding of aluminium and its alloys:

- A strong and tough oxide is very easily formed on the surface and can cause weld defects if not properly removed or broken up. The oxide has a low electrical conductivity.
- The aluminium oxide has a melting temperature of about 2060 °C, which is much higher than the melting temperature of pure aluminium at 660 °C. The oxide has a higher density than aluminium and may therefore remain in the melted aluminium and form slag inclusions in the solid material.
- Aluminium has a high solubility for hydrogen in the molten state but not in the solid phase. This will very easily lead to porosity since the hydrogen has insufficient time to disappear during solidification.
- The heat source for welding must be very intense depending on the high thermal conductivity of aluminium. MIG welding is therefore suitable.
- Aluminium has a low melting point and it is difficult to see when it melts since there is no colour change.
- There is no arc blow caused by the material itself since aluminium is non-magnetic. However, the arc can deflect considerably from the electrode direction. This may have different reasons. The electric current always chooses the easiest path (shortest or least resistance). The oxide layer also influences this behaviour. Magnetic fields generated by the current, the tilting of the welding torch and the connection of the return cable also have an influence.

14.3 Designation of aluminium alloys according to European standard

In this chapter only the numerical designation system for wrought alloys is discussed. These alloys are most often used for welding applications. The prefix AW is used which means a wrought product followed by a four-digit number. The first digit denotes the main alloying element(s),

- 1xxx Commercially pure aluminium

- 2xxx Copper
- 3xxx Manganese
- 4xxx Silicon
- 5xxx Magnesium
- 6xxx Silicon + magnesium
- 7xxx Zinc + magnesium
- 8xxx Others.

The group 1xxx is aluminium with a maximum of 1% of impurities. In this group the last two digits give the amount of aluminium, e.g. AW 1070 contains a minimum of 99.70% aluminium. In the other groups the last two digits are consecutive numbers. The second digit tells whether some adjustment of the composition of the original alloys in the groups has been made.

The alloys in the group 1 (pure aluminium), 3 (aluminium-manganese), 4 (aluminium-silicon) and 5 (aluminium-magnesium) are not heat-treatable. The alloys in group 2 (aluminium-copper), 6 (aluminium-magnesium-silicon) and 7 (aluminium-zinc-magnesium) are heat-treatable by precipitation hardening.

For the different alloys there is also a temper designation related to the conditions of delivery of the material, e.g. type of heat treatment, cold working, precipitation hardening.

- F – as fabricated
- O – annealed
- H – cold worked
- W – solution heat treated
- T – thermally treated, which means the state for alloys that are aged.

For the heat-treatable alloys the T-designation is followed by a digit to define in more detail the heat treatment sequence. Some examples are:

- T4 – solution heat treated and naturally aged
- T6 – solution heat treated and artificially aged
- T7 – solution heat treated and overaged or stabilised.

For detailed studies of the designations see the actual EN-standards. For example, EN 573 deals with the composition and designation of the alloys; EN 515 deals with the temper designations.

14.4 MIG welding of aluminium and its alloys

The wrought alloys in groups 1, 3, 5, 6 and 7 are generally considered to have a good weldability. By choosing the right joint configurations, the right welding parameters and filler materials, the welds will be good. The main rule is to use the same alloy in the filler material as in the parent material.

14.4.1 Joint types

Similar types of joints that are used for steel are also used for aluminium. Some of them are shown in Fig. 14.1.

Aluminium has some characteristics that are different from steel and influence the selection of joint configuration. The high coefficient of thermal expansion makes it difficult to weld some joints because of the distortions. A butt weld in thin aluminium may therefore be difficult to weld because of increasing gaps along the joint. It is necessary to fix the parts very carefully in a fixture to minimise the distortions.

For a butt weld in thick aluminium the joint angle in the V-joint must be bigger than for steel because the arc is not stable and will approach the closest part in the joint. That will give lack of fusion (see Fig. 14.2). This phenomena is not only a problem in V-joints but also in welding of filling joints where the arc has a tendency to go to the closest part or the part with the oxide layer that is easiest to break up. In a joint with different thicknesses of the parts, the arc has a tendency to heat the thinnest one most. This is compensated for by placing the electrode offset against the thickest part (see Fig. 14.3). The oxide has a high resistance and when the aluminium is heated it is easier for the arc to break the oxide. The oxide on the thinnest part is the easiest to break because it is easier to heat.

When welding thin aluminium in a lap joint with different thicknesses it is easier to have the thinnest one as the lower part (see Fig. 14.4) (for steel it is the opposite).

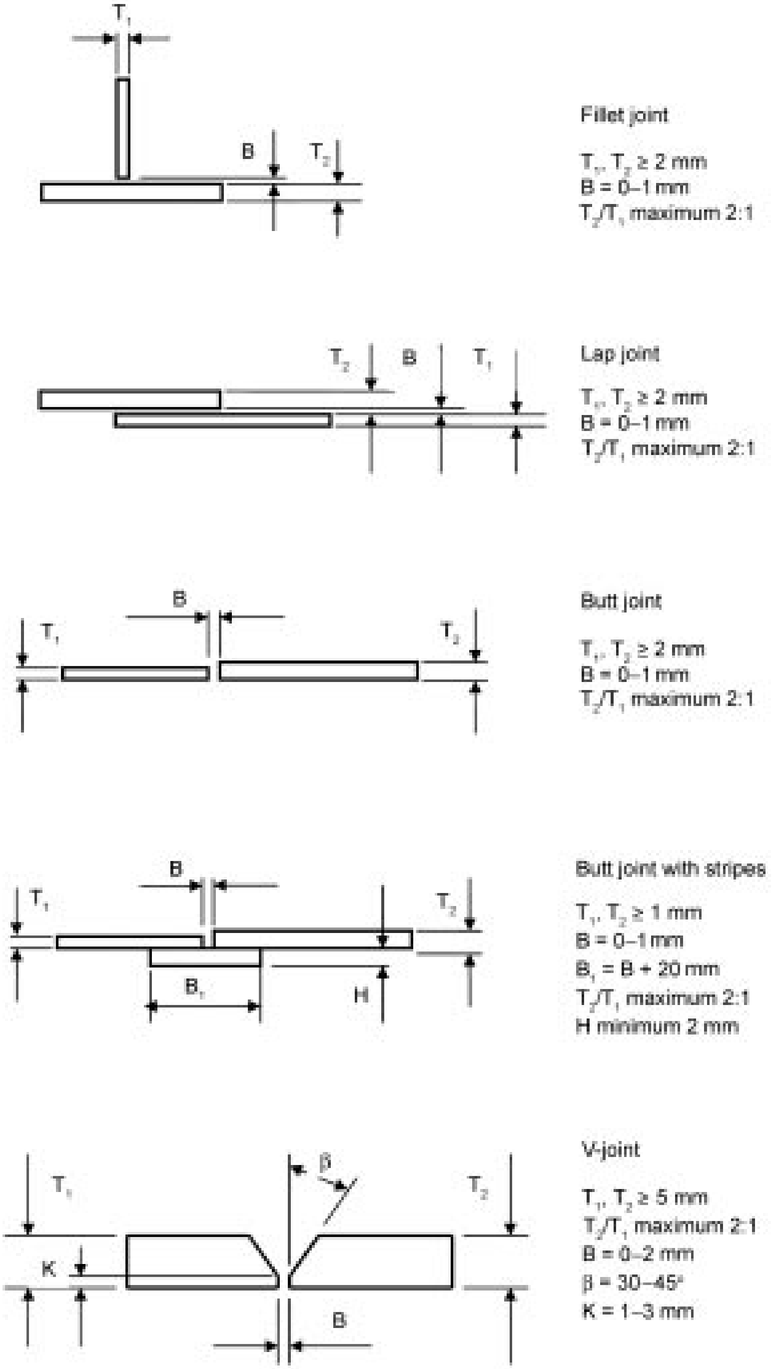
It is easier to weld aluminium in different positions compared to steel. One example is that it is rather easy to weld aluminium in position PE (overhead) or PF (vertical up). There may be more interruptions in the welding process because of spatter adhering to contact and gas nozzle. Another factor influencing the stability of welding is the soft filler wire that makes it more difficult to feed. The requirements on equipment are discussed in Section 2.6.

14.4.2 Filler materials and shielding gases

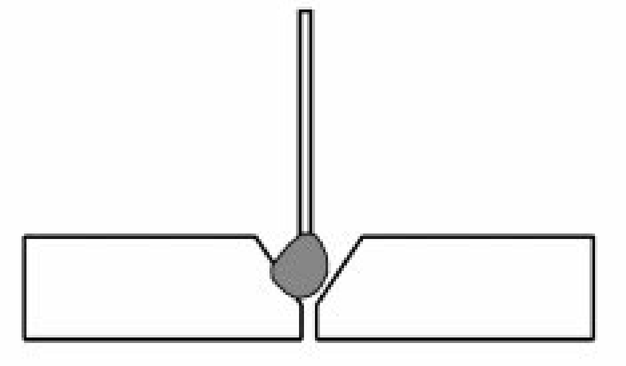
The filler material should give the material needed for the joint but will also add alloying elements to avoid hot cracking if this is a risk in the alloys or alloy combinations welded. The selection of filler materials for plate material and extruded profiles is shown in Table 14.1.

For AlMgSi-alloys the AlMg5 gives the best strength but AlSi5 gives the lowest risk of hot cracking and is more easily welded. For AlMg-alloys, use a filler material from the AlMg series. If good colour matching is needed after anodising of the material AlSi filler materials should not be used.

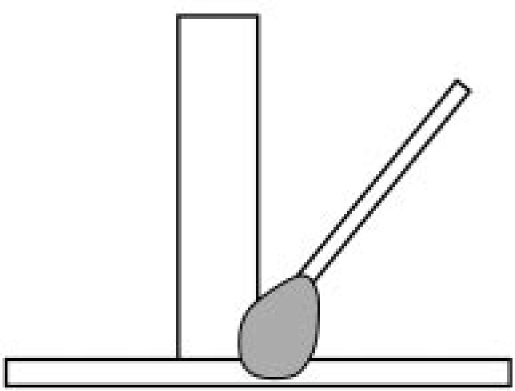
The filler material must be clean and stored in clean and dry places in unopened packaging. Filler wires can deteriorate and cause an instable arc and



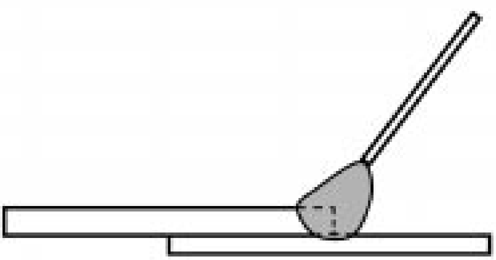
14.1 Types of joints in aluminium.



14.2 The arc from the electrode to the joint will go to the closest part of the joint.



14.3 Offset of the electrode against the thick plate.



14.4 For an overlap joint with different sheet thickness, the electrode is directed against the thicker plate.

Table 14.1 Recommendations for the selection of filler materials for welding of different aluminium alloys in plates or extruded profiles

Parent material A								
Al99.7	A199.8							
Al99.5 Al99.0	Al99.5Ti Al99.5	Al99.5Ti Al99.5						
AlMn	Al99.5Ti	Al99.5Ti	Al99.5Ti					
AlMg1 (Mn) AlMg2.5	Al99.5Ti AlMg5	Al99.5Ti AlMg5	Al99.5Ti AlMg5	AlMg5				
AlMg3	AlMg3 AlMg5	AlMg3 AlMg5	AlMg3 AlMg5	AlMg3 AlMg5	AlMg3 AlMg5			
AlMg4.5Mn	AlMg5	AlMg5	AlMg5	AlMg5	AlMg3	AlMg4.5Mn		
AlMgSi	AlMg5 AlSi5	AlMg5 AlSi5	AlMg5	AlMg5	AlMg5	AlMg5	AlMg5 AlSi5	
AlZnMg	AlMg5	AlMg5	AlMg5	AlMg5	AlMg5	AlMg5 AlMg4.5Mn	AlMg5	AlMg5 AlMg4.5Mn
Parent material B	Al99.7	Al99.5 Al99.0	AlMn	AlMg1 (Mn) AlMg2.5	AlMg3	AlMg4.5Mn	AlMgSi	AlZnMg

porosity if not sufficiently clean. The wires must also be free from moisture, e.g. from condensation. Wire cleaning devices can be used to remove grease, dust, etc. A special mechanical treatment called shaving is used during production of the wire. It not only removes the surface contaminants and oxides but also hardens the wire, which facilitates the feeding.

The most common shielding gases are argon and argon-helium mixtures. Helium increases the arc voltage and thereby also the energy transferred to the workpiece. The arc will also be broader. It is preferred for thick aluminium and there will also be fewer pores. Minor additions of active gases may in certain cases give a more stable arc. Higher productivity is possible with additions of 1% or more of oxygen to argon but the oxides both in the weld and on the surface will increase very much.

14.4.3 Pre-welding operations

The surfaces of the joints must be carefully cleaned before welding. Oil, dirt, grease, oxides and moisture on the surface as well as in the aluminium oxide layer must be removed. Otherwise the hydrogen formed in the arc at high temperatures dissolves in the molten pool and gives porosity. The amount of oxides in the weld is also decreased.

Mechanical as well as chemical methods can be used for cleaning of the material. The time before welding after cleaning must be minimised because the oxide layer immediately increases again. It is important to rinse and dry the material just before welding.

14.4.4 The strength of the weld after welding

The heating during welding influences the material surrounding the melted material. The weld metal has an as-cast microstructure mainly influenced by the filler material and its dilution with the base material that has been melted. In the HAZ there will be a heat treatment of the microstructure. If it has been in an annealed state the strength has not been lowered, but if it has been in a cold-worked or precipitation-hardened state the strength decrease can be fairly large. The width of the zone can also be rather big. For the cold-worked material there will be recrystallisation already at temperatures exceeding 200 °C. In the hardened alloys the microstructure will be over-aged, that means a coarsening of the particles leading to a decrease in the high strength of these types of alloys.

Some of this strength loss can be regained by natural ageing or artificial ageing but only if the base metal is welded in an aged condition. During welding some parts of the HAZ get a solution treatment. In the following rapid cooling from the welding temperature some of the elements will be retained in solid solution and hardening will be possible by ageing. In an over-aged condition there will be no or minor strength increase since there is not enough time for dissolving the coarse particles.

14.4.5 Deformations caused by welding

In order to minimise the effects of the high heat-induced deformations one must follow the general rules with low heat input and high welding speed as well as heating as symmetrically as possible. It is also preferable to weld from the centre towards the ends of the workpiece.

14.4.6 Welding procedures

Normally spray arc or pulse arc (for thinner materials) shall be used. The heating is more effective than with short arc and lack of fusion is avoided. Special care has to be taken in the start of the weld. The welding gun should be directed 10°–25° in the forehand direction (pushing). This provides better cleaning from oxides and better gas coverage. The wrong angle can cause air entrainment in the shielding gas.

The stick-out should be between 10 and 20 mm. With helium additions in the shielding gas the stick-out should be shorter and the forehand angle somewhat bigger.

If the welding parameters are wrong there will be a blackening of the weld and the surrounding material. This is caused by aluminium and magnesium oxides that are attached to the surface. Optimisation of the welding parameters and the angles decreases the blackening.

The fast metal transport in the arc makes it possible to use MIG welding in all positions.

14.4.7 Welding equipment

There are some special precautions to be considered regarding the welding equipment to be used.

Both normal short/spray arc and pulsed arc must be available in the power source. Pulsed arc is used for thin material up to a thickness of about 3 mm. Pulsed arc welding also makes it possible to use wires with higher diameters. These wires give less spatter and more stable feeding.

It is also advantageous to have the possibility to use special programmes for the starting and ending of the weld to avoid weld defects.

The wire feed system must be able to feed the aluminium wires that are softer than steel wires. The wire drive rolls should not deform the wire and therefore a four-roll wire drive unit is often used. Too hard a pressure can lead to small fragments of wire coming into the wire feed liner and the feeding being disturbed. Too long hoses often cause problems and extra feeding systems or push-pull systems must be used. The liner should be made of soft material, i.e. plastic instead of steel to reduce the friction and the risk for iron contamination. The wire feed system must also be properly protected from dust, moisture, etc.

The welding gun should be water-cooled or have a special design to keep the temperature low. The contact tips have to be as big as possible, 10 mm diameter is to preferred but 8 mm also works if the welding gun is carefully cooled.

14.5 Future trends

The use of aluminium increases but is much dependent on the actual prices. Fusion welding is fairly difficult, especially for high-strength alloys. This means that competing processes to MIG welding are appearing. Examples of such processes in the automobile industry are mechanical joining and laser welding. Combinations of press-cast node structures with extruded profiles are also advantageous to avoid welding in the most critical regions of the constructions.

For heavier constructions friction stir welding has also recently been used.

14.6 Bibliography

Mathers, G. (2002) *The welding of aluminium and its alloys*. Woodhead Publishing, Cambridge.

Mattsson, S. (2001) *SIS Handbok 12 Aluminium*. SIS Förlag AB, Stockholm (in Swedish).

15

Robotic equipment for MIG welding

D SKARIN, J NILSSON and D GREEN,
ABB Automation Technologies AB, Sweden

15.1 Introduction

An industrial robot is officially defined by ISO (Standard 8373:1994, Manipulating Industrial Robots – Vocabulary) as an *automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes*.

The robot is the main part of the production cells for MIG welding. It has replaced the automated equipment aimed for larger series by its high flexibility in mobility patterns and reprogramming possibilities. It is a very effective and flexible device with which to move the welding gun along the weld seam.

Robotic welding is today recognised as a mature production method and has for many years been used by a large number of companies in MIG welding. However, at the same time both MIG welding and other arc welding methods are still performed manually. A rough estimation is that less than 10% of all arc welding operations, measured as deposited weld metal, all over the world, are using robots.

This means that the overall potential for introducing robotic MIG welding is substantial even if welding is partly replaced by other methods and new materials not requiring welding. The challenge for industries producing welded products is to produce in a more cost efficient way than before. One possibility is to utilise the latest arc welding automation technologies and equipment on the market. Robotic arc welding, in particular, is here playing an important role.

Some characteristics of the robot itself with special regard to MIG welding are:

- A flexible movement pattern using at least five axes.
- A large working space.
- High repeatability and accuracy of positioning, which is needed for MIG welding.
- High accuracy in welding speed.
- High speed in the transfer between different welds.
- Good control of acceleration and deceleration.

- Advanced computerised programming with many special solutions for MIG welding applications.

This chapter will not go into details of the robots themselves. For further information general textbooks on robots are recommended. There will only be a short introduction regarding the history of robots in arc welding. As the workpiece positioner is another main part in automated MIG welding stations a separate section (15.3) will discuss this. The chapter will then concentrate on the different production concepts used for robotic MIG welding and some auxiliary equipment necessary to build an efficient and safe robot cell. Offline programming of robots will also be discussed.

15.1.1 Historical background of industrial robots

The name *robot* was originally used to describe an automated humanoid machine, but within the world of technology science the word has a much wider application scope. Within the industry the name *robot* could apply to many different automated systems, from the most simple ones to the most complex ones. The word *robot* has its origin from an old German word *robat*. In the Polish and Czech languages this word survived as *robota* meaning *the compulsory labour*. Isaac Asimov, the science fiction writer, was the first one to use the word *robotics* to describe robot technology.

Robotic history had already started in 1961, when Joseph Engelberger together with George Deroe developed the first commercial hydraulic robot, Unimate. This first robot was used in the Ford factories for loading of a press. The real breakthrough of this new invention for industrial use came three years later in 1964 when General Motors in Lordstown (Ohio) ordered 66 Unimate robots for their production. Another three years later in 1967 the first hydraulic Unimate robot was delivered to Europe to the Swedish company Metallverken in Upplands Väsby outside Stockholm.

In 1969 General Motors invested in Unimate robots a second time for spot welding and for the first time they also invested in Tralfa robots from Norway for painting.

At the beginning of the 1970s the Swedish company ASEA started the development of robots and in 1973 the first electrically controlled robots on the world market for industrial use were presented. In 1974 the first robot of this type was delivered from ASEA to a Swedish company for grinding and polishing of small metal tubes. The same year the second robot was delivered, this time for MIG welding.

This first electrical robot was equipped with five free programmable axes and had a maximum payload of 6 kg, controlled by an Intel 8008 CPU computer with a total storage capacity of 8 Kb of software code.

The above-mentioned pilot developments started an intensive activity all over the world during the next ten years, which resulted in many new types of electrical, microcomputer-controlled robots being built by a lot of companies. Some of the main companies that were active on the robotic market during this period were in Japan, such as:

- Fanuc & Siemens
- Kawasaki
- Nachi
- Yaskawa

And in Europe:

- ASEA
- Kuka
- Renault, Acma
- Volkswagen
- FIAT, Comau

The intensive worldwide market introduction of robot technology during the 1980s and the hard competition on the market have had an important impetus for the development of the advanced robot systems that are available today, and, in particular, for MIG welding as this is one of the most demanding robotic applications.

Today the five largest manufacturers of robots for arc welding, mainly MIG welding, are:

- Yaskawa
- ABB
- OTC
- Panasonic
- Fanuc

There are also many companies integrating these robots into their robotic cells which are then delivered to the welding industry. In the next section different segments of industry using robotic MIG welding will be presented.

15.2 Types of industries using robotic arc welding

The general view is that robotic arc welding is most suitable for applications within the automotive industry and for high volume production. This is not correct as we know that robotic arc welding is a widespread technology and has successfully been implemented in many different segments outside the automotive industry. One very good and extreme example is one-piece robot arc welding production of superstructures within the shipbuilding industry.

Some important industrial segments using robotic MIG welding are industries producing:

- Automotive and automotive parts
- Non-automotive vehicles
- Subcontractors
- General metal industry
- Infrastructure

Automotive and automotive parts

Common products and parts within this segment are, seats, axles, exhaust systems, suspension frames, tow bars, roof racks, etc. The main characteristics in this segment are:

- New materials
- High volume
- Robot intensive
- Redefined production methods
- Short cycle times
- Space intensive

Non-automotive vehicles

Common products within this segment are, off-road and industrial vehicles, buses, trailers, trucks, vehicles for farming, rolling stock, etc. The main characteristics in this segment are:

- Large frames
- Many components
- Extensive production range
- Complex welding
- High loads/stresses
- Repetitive production
- Low batch production

Subcontractors

Common products within this segment could be smaller parts for the non-automotive industrial sector. The main characteristics are:

- Mixed production
- Mixed complexity
- Low batches
- Fluctuating orders that need flexibility
- Low robot density

General metal industry

Within this segment there are many different producers with many different products and parts that could be considered to be welded by robots from steel furniture, bicycles to steel cabinets, etc. The main characteristics in this segment are:

- Less complexity
- Short cycle times
- High and low volumes
- Short, long and circular welds

Infrastructures

Common products within this segment are ships, off-shore constructions, bridges, large cranes, building construction parts, etc. The main characteristics in this segment are:

- Logistic
- One-piece production
- Large stock level
- Low robot density

Summary

Depending on the applications the requirement on the production concepts will differ. The different concepts will be discussed in Section 15.4.

15.3 Workpiece positioners

A workpiece positioner is a tool that manipulates the workpiece and is used for manual welding as well as robotic welding. For robotic welding stations the positioners are necessary for high uptime and productivity as well as safety. If the workpiece is fixed, the robot may not be able to reach all of the weld joints without manual repositioning of the workpiece, which will considerably reduce the output from a robot welding station.

This guide gives some basic information about positioners and how to select the most suitable positioner. A workpiece positioner gives the following benefits:

- Increases accessibility of the joints to be welded.
- Makes it possible to weld in the flat position, which is particularly important when making large welds with big throat thickness.
- Increases the welding speed by positioning thinner workpieces so that welding slightly vertical down is possible.

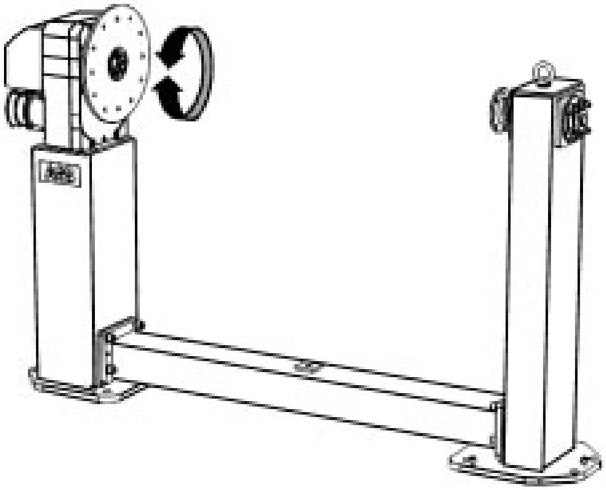
- Allows the use of the two station working principle with robot welding while the operator is unloading and loading on the opposite side.
- Protects the operator from the arc radiation and spatter.
- Reduced re-orientation of the robot – cycle time reduction and reduced wear on the torch hose assembly.
- Improves ergonomics for the operator.

15.3.1 Types of positioners

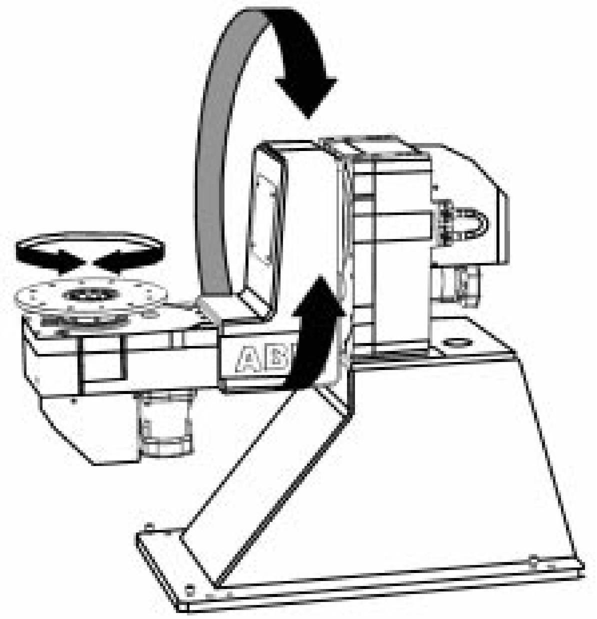
There is a wide range of workpiece positioners available, from indexing tables to multi-axes positioners with station interchange. The most common types have the following configurations.

- Fixed table
- One-axis positioner (Fig. 15.1)
- Two-axes positioner (Fig. 15.2)
- Table with station interchange (Fig. 15.3)
- One-axis positioner with vertical station interchange (Fig. 15.4)
- One-axis positioner with horizontal station interchange (Fig. 15.5)
- Two-axes positioner with station interchange (Fig. 15.6)

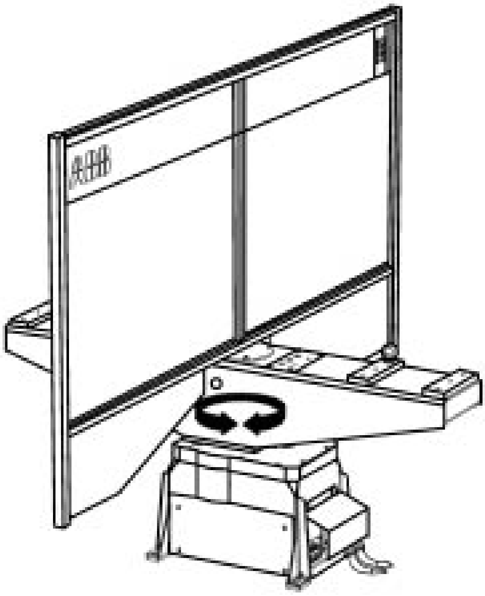
The handling capacity of standard workpiece positioners is from 100 kg to around 5 tonnes. In addition to these standard designs there are many purpose-built positioners available on the market that can have a capacity of up to 50 tonnes or more. The majority of workpiece positioners for robot applications are controlled from the robot system. Independently controlled positioners still exist



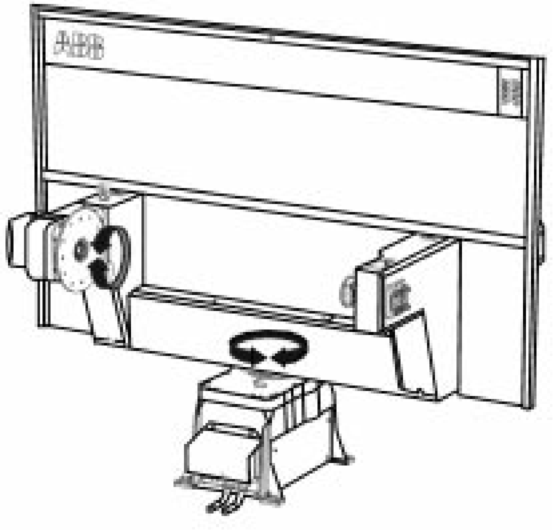
15.1 One-axis positioner.



15.2 Two-axes positioner.



15.3 Table with station interchange.

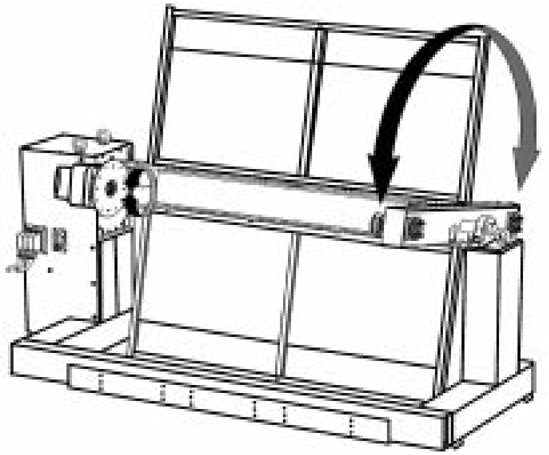


15.4 One-axis positioner with vertical station interchange.

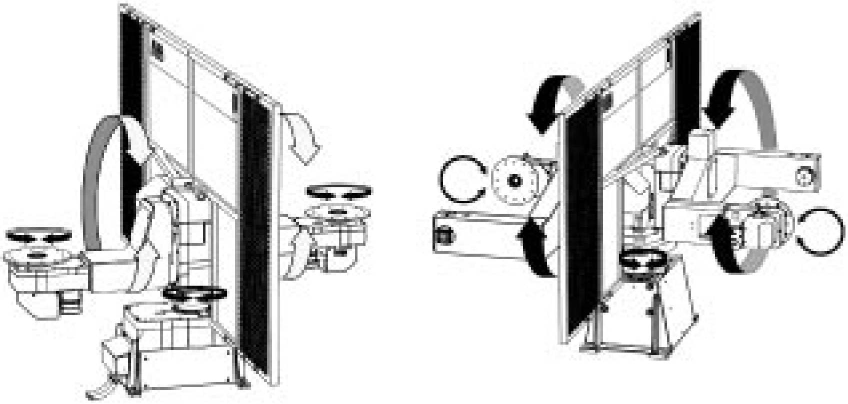
and are usually controlled from external drives. Small tables with a station interchange are sometimes manually operated.

When discussing robots and positioners it is important to mention the general nomenclature for the axes.

Robot axes = *Internal axes*
Positioner axes = *Additional axes*



15.5 One-axis positioner with horizontal station interchange.



15.6 Two-axes positioner with station interchange.

15.3.2 Programming and operation

Kinematic integration of additional axes with internal axes is very important for the user and the performance of the positioner. This type of integration significantly reduces the total cycle time because the robot does not have to wait for signal communication from the positioner control.

The level of integration can be arranged as shown in Table 15.1, starting from no kinematic integration to a high level of kinematic integration.

15.3.3 Selection criteria for workpiece positioners

To select an appropriate workpiece positioner certain criteria should be considered.

- Is manipulation of the workpiece required? For example, no manipulation at all, one-axis manipulation or two-axes manipulation?
- Is a supporting tailstock required? For example, is the fixture sufficiently rigid to be mounted from one side only or is a supporting tailstock required?
- Is the fixture rigid enough for the positioner? For example, can the selected type handle the bending moment?
- Required floor space? For example, will the robot welding station fit in the existing workshop layout?
- Which design fits in the existing production flow? For example, are one or two working areas required to optimise the production flow?
- Can the positioner be used for future products? For example, is the degree of manipulation, loading capacity and handling volume sufficient?

Table 15.1

Solution	Comments
Fixed table	Positioning of the workpiece is not possible.
Indexing positioner	The positioner is controlled by external control equipment. Indexing of the workpiece is possible. While indexing, the robot has to stop welding and reverse from the positioner to a safe position, which increases the total cycle time. Initialisation of the indexing is set from the robot program.
Servo-controlled positioner	The positioner is controlled from the robot control system and its position and speed is controlled from the robot program. Coordinated motion between internal and external axes is possible if the programmed weld path is split into small segments. This programming procedure is called 'time positioning', which is difficult to program, maintain and is very time consuming. The path accuracy depends on the number of segments and accuracy of programming.
Servo-controlled positioner with integrated additional axes	The positioner is fully controlled from the robot control system with the position and speed controlled by the robot program. The integration of the additional axes gives true coordination between the internal and additional axes. The programmer programs the desired welding path and speed and the robot control system ensures precise path-following accuracy along the weld seam.
Servo-controlled positioner with integrated additional axes and load identification	A modern method to improve the path accuracy and reduce time for positioning of the workpiece is to introduce a dynamic model which automatically identifies the mass and centre of gravity of the workpiece. With the implementation of load identification the required time for acceleration and deceleration is reduced considerably with even better path accuracy.

Positioner A: Fixed table

This type is sufficient when no manipulation of the workpiece is required. It is common to have more than two working positions for such solutions.

Positioner B: One-axis positioner

This is necessary when one-axis manipulation of the workpiece is required. This type of positioner is available with or without the supporting tailstock. Versions with a horizontal face-plate are also quite common.

Positioner C: Two-axes positioner

The reasons for using a two-axes positioner are primarily:

- Accessibility of the joints.
- The size of the weld pool requires welding in flat position.
- Increased flexibility for future products.

The two-axes positioners are designed with or without a supporting tailstock depending on the tooling and the workpiece.

Positioners D, E and F: Workpiece positioners with station interchange

The station interchange gives the dual operation principle on less floor space compared to separate tables/positioners. The degree of freedom is the same as for the positioners A, B, and C. It gives ergonomic advantages for the operator with only one area for loading and unloading, a very important factor if the cycle time is short.

The positioners E and F are both of the one-axis type, but the station interchange unit is arranged in different ways. Positioner E interchanges around a vertical shaft while positioner F interchanges around a horizontal shaft.

Positioner E is sufficient when the workpiece is relatively small, with a length of up to approximately two metres and diameter slightly more than one metre. The reason is that the required distance between the robot and workpiece positioner increases greatly for long workpieces when the positioner performs the station interchange. Too long a distance between the robot and fixture results in a problem for the robot to reach the entire workpiece. One solution is to use a column with a suspended robot above the positioner.

For long workpieces the F-type of positioner is preferable because the robot can be located close to the positioner. The diameter of the workpiece is the only limiting factor for the working envelope of the robot.

To keep a low load/unload height on the operator side, the corresponding height on the robot side will be high. This is something to consider, because programming cannot be done at floor level. On station interchange this type of positioner will turn the tooling and workpiece upside-down. If the workpiece can easily be loaded–welded–unloaded from both sides, this is not a problem. If not, extra positioning will be required which increases the total cycle time. There are positioners available on the market today, which turn all axes during station interchange that present the workpiece in optimum position for the operator and robot.

When is it preferable to use positioners without the station interchange? The dual operation principle gives great advantages in production output and ergonomics, but sometimes it is preferable to use separate positioners with separate working areas. Some examples are:

- Very big difference in weight of tooling or workpiece between the two stations.
- The total weight and volume of the workpiece.
- Very big difference in loading time between the two workpieces.
- If the tooling is changed frequently, the production can still continue on the other station.

For big workpieces such as frames for off-road vehicles or other big structures, the robots are mounted on travel tracks or gantries to maintain the dual operation principle.

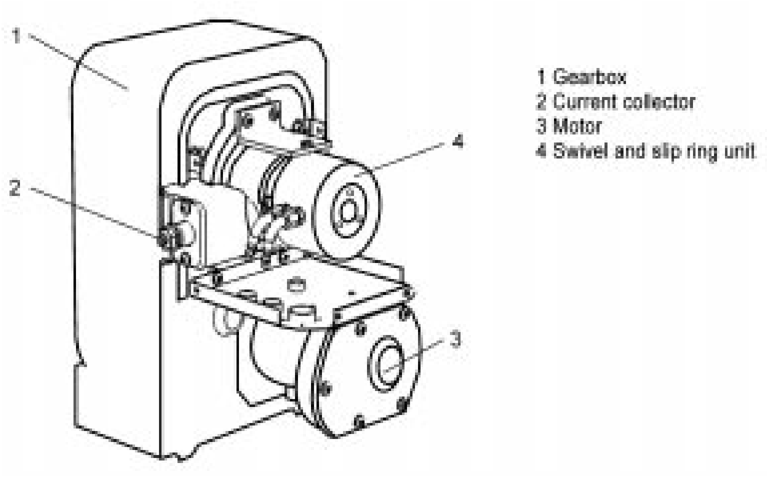
15.3.4 Media supply to the tooling

Modern automatic tooling requires media supplies. The media transferred from other equipment to the tooling can be:

- Weld return.
- Compressed air or hydraulic oil for the clamping devices.
- Electrical signals for valves or sensors.
- In some cases, cooling of the tooling.

The media is transferred through the positioner structure using current collectors for the weld return, swivels for compressed air/oil/cooling liquid and slip rings for the electrical signals. Figure 15.7 shows the arrangement of media supplies on a positioner gearbox.

When two robots are welding simultaneously on the same workpiece is it important to use two isolated current collectors for welding return, one on the



15.7

headstock and one on the tailstock. This is to achieve an even distribution of the welding current in the workpiece with preferential current paths, which reduces the risk of interference between the two arcs.

15.4 Robotic production concepts

The production concepts are very much related to the product and the type of production for which the robot system will be used. Some important points to consider before selecting a suitable arc welding robotic production concept for a specific application are:

- Large series or batch production?
- Large, medium, small batch production, or one-piece production?
- Long (hours), medium (minutes) or short (seconds) cycle time per operation?
- The part geometrical dimensions.
- The weight of parts and workpiece.
- The product complexity.
- Tack welding and final welding in one or two operations?
- The fixture complexity – holding fixture or welding fixture for both tack welding and final welding in one fixture?

Depending on the result of the evaluation there are several main robotic production concepts to choose between:

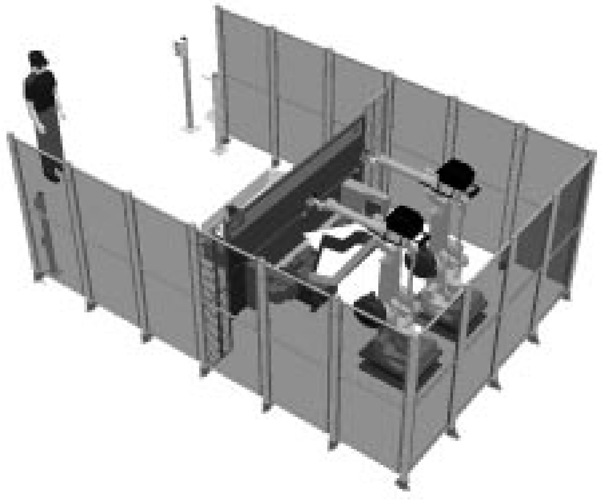
- Cell concept (Fig. 15.8)
- Multi-index cell concept (Fig. 15.9)
- Transfer line concept (Fig. 15.10)
- Flexible positioner cell concept (Fig. 15.11)
- FMS (flexible manufacturing system) concept (Fig. 15.12)
- Rotating/travelling column and stationary gantry cell concept (Figs 15.13(a,b and c))
- Portable/mobile robot concept (Fig. 15.14)

The different main production concepts can also be combined, but it is most common to select one of these concepts.

Here are some short descriptions of the different robot production concepts and which type of product and production they are most suitable for.

15.4.1 The 'cell concept'

The 'cell concept' is often based upon a 'two station' concept where the robot is welding on one side and the loading and unloading are performed on the other side. It is most common that the loading and unloading of the parts are performed manually, but in some cases this operation is performed by the arc welding robot (equipped with extra gripper), or another dedicated handling



15.8 Cell concept.

robot. In some cases in a ‘cell concept’ for welding of large parts, the robot could be mounted on a track on the floor or in an upside-down position in a fixed or rotating column or, alternatively, in a fixed gantry system. However, these larger systems are still to be treated as ‘cell concepts’.

The ‘cell concept’ normally consists of the following main equipment:

- One or two arc welding robots, including control system and software.
- One servo-controlled track, or fixed or rotating column, if required owing to the size of the product.
- Workpiece positioner(s), with one or two work stations.
- Arc welding process equipment, e.g. power source, wire-feed system, welding torch.
- Safety equipment, operator panel, light beams, gate switches, reset units and fences.

These types of ‘cell concepts’ are most suitable for large and medium batch production, but could also be used for mass-production, if a short total lead-time does not have the highest priority. A typical ‘cell concept’ is normally also suitable for very large and heavy products with long cycle times.

Some examples of typical products where the ‘cell concept’ is suitable:

- Automotive parts
- Two-wheelers (bicycles/motor cycles)
- Industrial vehicles
- Trucks and busses
- Off-road vehicles
- Agriculture vehicles and equipment

- Steel furniture
- Cabinets
- Basic metal products

Benefits

The ‘cell concept’ is easy to understand and operate. The ‘cell’ is easy to multiply if more production capacity is needed. An extra robot could be added to operate towards the same positioner to increase production capacity. It is flexible for the introduction of other types of products.

Disadvantages

The ‘cell concept’ has low lead-time flexibility when producing in large and medium batch production. Depending on the individual set-up times, the total lead time for a family of products could be longer than with other production concepts.

15.4.2 The ‘multi-index cell concept’

The ‘multi-index cell concept’ is often based upon four stations, where three of the stations are for robot welding and one station is for the loading/unloading operation. The most common is that the loading/unloading of the parts are performed manually, but in many cases this operation is done by a dedicated handling robot.

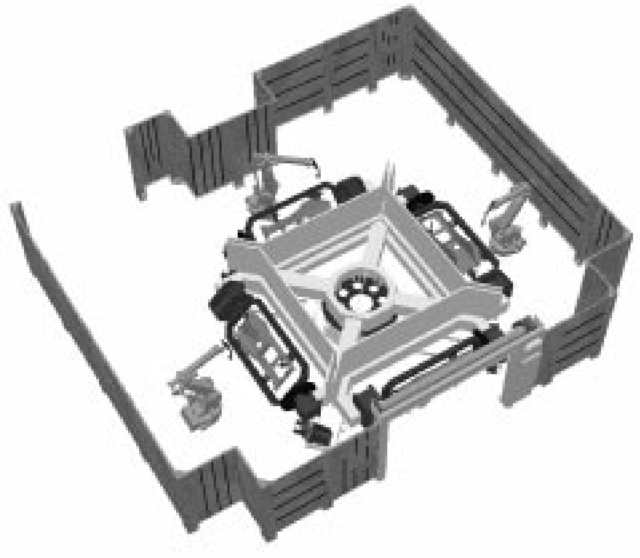
The ‘multi-index cell concept’ normally consists of the following main equipment:

- Three to six arc welding robots, including control system and software.
- Workpiece positioner, with three to five working stations.
- Arc welding process equipment, e.g. power sources, wire-feed systems, and welding torches.
- Safety equipment including operator panel, light beams, gate switches, reset units and fences.

These types of ‘multi-index cell concept’ are most suitable for mass-produced products, where short lead times per cell have a high priority. The concept can also be used for large batch production, when lead time has lower priority.

Some examples of typical products that are suitable for the ‘multi-index cell concept’:

- Automotive parts
- Two-wheelers
- Steel furniture
- Other mass-produced steel products



15.9 Multi-index cell concept.

Benefits

The 'multi-index cell concept' is quite easy to understand and operate. The 'cell' is easy to multiply or more robots could be added in the cell if more production capacity is needed. It is quite flexible for the introduction of other types of products. This concept has higher lead-time flexibility when using it for mass production, compared to the 'cell concept'.

Disadvantages

As more robots are involved in the complete cell it is more sensitive for individual breakdowns, which can have a negative effect on the total up-time in the station. When using it for large batch production, the set-up time is often longer than if the same product should be welded in a 'cell concept'.

15.4.3 The 'transfer line concept'

The 'transfer line concept' is often based on a single line where the products are transferred through a number of different working stations and are completed at the end of the line. The 'transfer line concept' normally consists of the following equipment:

- A number of arc welding robots, including control system and software.
- Transfer carriage or handling robots moving the parts forwards from station to station.

15.10 Transfer line concept.

- Arc welding process equipment, e.g. power sources, wire-feed systems and welding torches.
- Safety equipment including gate switches, reset units and fences around the whole transfer line.

These types of 'transfer line concepts' are most suitable for mass-produced products, where short lead times and high output capacity have very high priority.

Some examples of typical products that are suitable for the 'transfer line concept':

- Automotive car bodies
- Automotive parts
- Steel furniture
- Other mass-produced steel products

Benefits

The 'transfer line concept' has high lead time and cycle time flexibility, as more robots could be added in the line if shorter lead time and cycle time are required.

Disadvantages

The 'transfer line concept' is very sensitive for individual breakdowns, which can have very negative effects on the total up-time in the line. The requirement on the robot supplier to have high MTBF (mean time before failure) and low MTTR (mean time to repair) figures will become very important.

15.4.4 The 'flexible positioner cell concept'

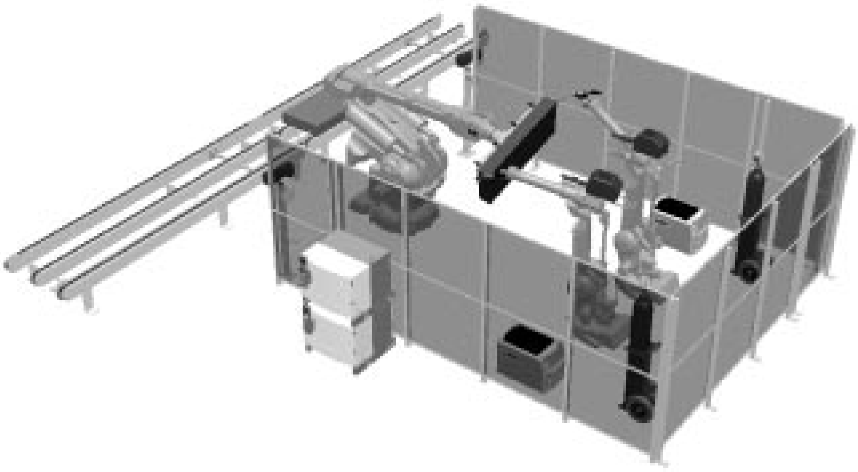
The 'flexible positioner cell concept' is based on several robots which are working together, where one of the robots is holding the product, and the other arc welding robots are welding the product. The robot that holds the product is often a large robot with a high load capacity, and this robot is also taking care of loading and unloading of the product from or to a storage or a roller conveyor system.

The 'flexible positioner cell concept' consists normally of the following equipment:

- Two arc welding robots, and one handling robot, including control system and software.
- No workpiece positioner is included in this concept.
- Arc welding process equipment, e.g. power sources, wire-feed systems and welding torches.
- Safety equipment.

These types of 'flexible positioner cell concept' are most suitable for large and medium batch production, but can also be used for mass production. This cell concept can also be combined with the 'transfer line concept', giving the possibility to reduce the lead time even further.

Some examples of typical products that are suitable for the 'flexible positioner cell concept':



15.11 Flexible positioner cell concept.

- Automotive parts
- Two-wheelers
- Steel furniture
- Other mass-produced steel products

Benefits

The 'flexible positioner concept' gives very high flexibility in finding solutions where the loading and unloading operation can be fully automated. If the robot system is equipped with simultaneous and coordinated capabilities, the welds on the product can be programmed to the optimum position.

Disadvantages

As the 'flexible positioner concept' often includes several robots that need to work together it is sensitive for individual breakdowns, which can have a negative effect on the total up-time in the cell. The requirement on the robot supplier to have high MTBF (mean time before failure) and low MTTR (mean time to repair) figures will become important.

15.4.5 The 'FMS (flexible manufacturing system) concept'

The 'FMS concept' consists of one or several robots that are connected to a roller conveyor system. The roller conveyor system is often equipped with an automatic controlled carriage that is normally made for handling standard 'Europallets' (1200 × 800 mm), on which the different products are placed. Each individual 'pallet' with a fixture has a unique bar code, which is read automatically by the robot system. The actual robot program for the welding is then loaded into the robot control system. The positioner(s) in this system is/are equipped with an automatic docking mechanism, in which the standard pallet is clamped in position for welding.

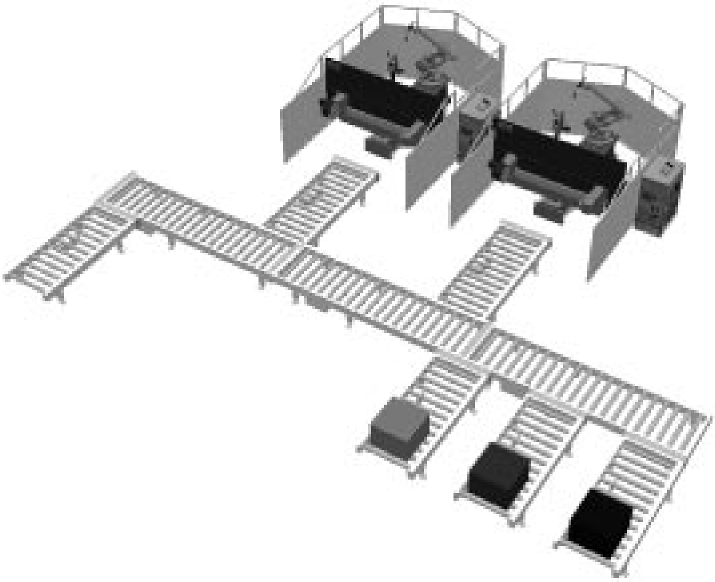
The 'FMS concept' comprises the following equipment:

- One or several arc welding robots, including control system and software.
- One or several workpiece positioners, with automatic docking device.
- Arc welding process equipment.
- Safety equipment including operator panels for each loading/unloading station, gate switches, reset units and fences around the whole FMS station.

The 'FMS concept' is most suitable for small batch and one-piece production, but can also be used for medium batch production.

Some examples of typical products that are suitable for the 'FMS concept':

- Off-road vehicle parts
- Industrial vehicle parts



15.12 FMS (flexible manufacturing system) concept.

- Agriculture vehicle and equipment parts
- Parts for trucks and busses
- Other low series-produced products

Benefits

The ‘FMS concept’ has very high flexibility regarding both products and different solutions in which the loading and unloading operation is fully automated. The set-up time between different products is more or less eliminated, which gives the user the possibility of also running one-piece production. As the handling and docking into the workpiece positioner is performed automatically, the system can be running ‘unmanned’ for many minutes or up to several hours depending on product complexity and capacity of the selected conveyor system.

Production can be carried out on customer orders with a short lead time. The operator is independent of the actual robot welding station, which can give a positive effect on the work environment of the operator. If the ‘FMS concept’ is used in the optimum way in combination with operations before and after welding it can dramatically reduce the total cost for products in stock.

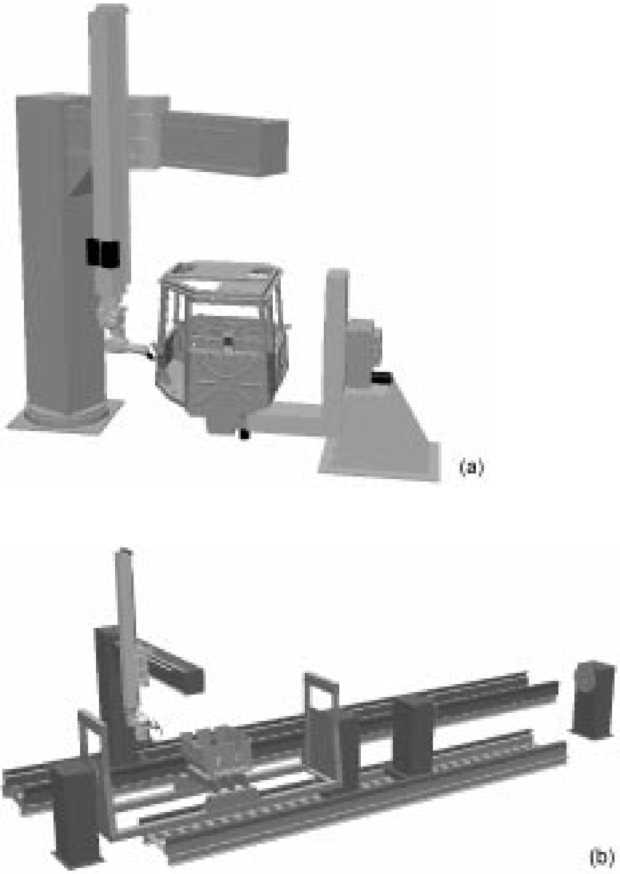
Disadvantages

The investment cost for the ‘FMS concept’ is normally higher calculated per working welding arc compared to the ‘cell concept’. This could be seen as an initial problem since the total product production cost per part is shown to be lower in the end.

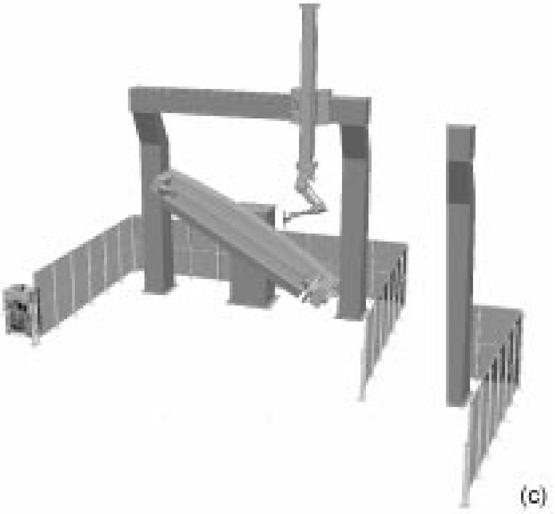
15.4.6 The 'travelling column and gantry concept'

The 'travelling column and gantry concept' uses a column with a hanging robot on a servo-controlled track or a gantry placed on a rail system. Normally there are two working stations (one for robot welding and one for loading and unloading) in front of the travelling column track or under the travelling gantry. Each working station can be equipped with fixed tables, or workpiece positioners.

The 'travelling column and gantry concept' most often consists of the following main components:



15.13 (a) Rotating column; (b) travelling column; (c) stationary gantry.



15.13 continued

- One or two arc welding robots, including control system and software.
- One servo-controlled travelling column or gantry system.
- Fixed tables alternatively one or two workpiece positioners.
- Arc welding process equipment.
- Safety equipment including operator panels for each loading/unloading station, light beams, gate switches, reset units and fences.

The 'travelling column and gantry concept' is most suitable for medium and small batch production. One-piece production is also possible if the robot system is equipped with powerful off-line programming software.

Some examples of typical products that are suitable for the 'travelling column and gantry concept':

- Off-road vehicle frames and cabinets
- Industrial vehicle frames and cabinets
- Agriculture vehicle frames and cabinets
- Frames and cabinets for trucks and busses
- Ship panels, double bottom structures and tunnel thrusters
- Boilers
- Other large product structures

Benefits

The 'travelling column and gantry concept' has very high working range and work position flexibility. High arc time is achieved thanks to relative fast motion between weld positions.

Disadvantages

Large systems like these can be very difficult to program online, since the products are normally very large. This means that the programmer often needs to climb on the product to be able to create a welding program.

15.4.7 The 'portable/mobile robot concept'

The 'portable/mobile robot concept' consists of a robot mounted on a platform or carriage that can be moved to different locations in which the welding operation should be performed.

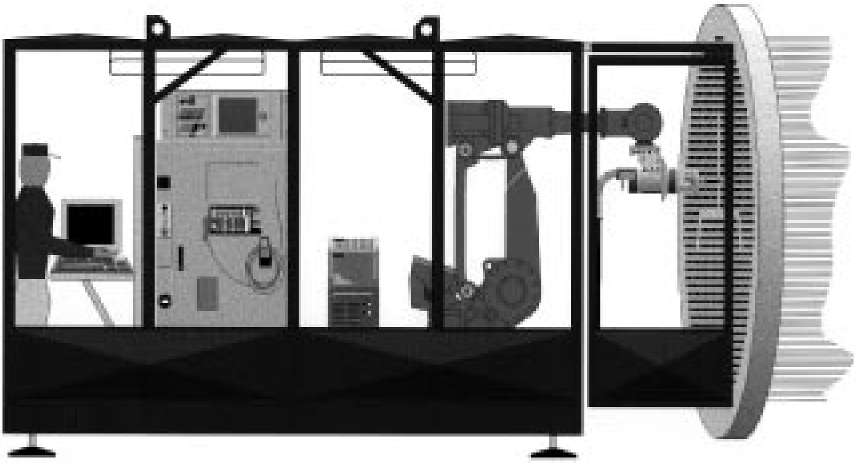
The 'portable/mobile robot concept' normally includes the following main equipment:

- One arc welding robot on a platform or a carriage, including control system and software.
- Fixed tables or fixed positioners on which the products are placed.
- Arc welding process equipment.
- Safety equipment integrated on the robot platform or on the carriage.

The 'portable/mobile robot concept' is most suitable for very large products that are difficult to move in the production facilities.

Some examples of typical products that are suitable for the 'portable/mobile robot concept':

- Boilers ('tube to sheet' welding)
- Ship panels and double bottom structures



15.14 Portable/mobile robot concept.

Benefits

The ‘portable/mobile robot concept’ is cost efficient if the arc time is relatively long after each movement of the robot platform/carriage and its working envelope.

Disadvantages

The production capacity will go down dramatically if the arc time in each new position of the robot platform/carriage is too short.

15.5 System integration

There are different levels of robot system integration to consider when investing in arc welding robot systems. The different levels of integration will also lead to different advantages and disadvantages that will affect the total economy and lifetime of the investment.

The following equipment and software tools can be included in a complete arc welding robot system:

- Arc welding robot, handling robot, etc.
- Workpiece positioner(s)
- Fixtures for the part(s) to be welded
- Arc welding equipment including power source, wire-feed system, welding torch assembly
- Tool service centre including torch cleaner, wire cutter and tool calibration system
- Sensors for searching:
  - Mechanical tactile sensor
  - Electrical tactile sensor
  - Optical sensor

  Sensors for tracking:
  - ‘Through the arc’ sensor
  - Laser sensor
- Safety system including light beams, gate switches and reset units
- Software tools: offline motion simulation and programming, MIG/MAG process simulation and prediction, etc.

One way to know which types of equipment and system integration are needed for a specific arc welding production is to have direct contact with one or several arc welding robot suppliers or some robotic arc welding integrators on the market.

In the following sections the integration of some important equipment and software of special interest for MIG welding will be discussed in more detail.

15.5.1 MIG welding equipment

The main questions to be put before selecting the MIG/MAG welding equipment for a specific weld application could be the following:

- Is the selected MIG/MAG welding equipment suitable and reliable for robotic welding?
- Is the duty cycle, voltage and current output enough for the application?
- Is the welding equipment easy to program together with the robot?
- Are one or more programming units needed to program the process equipment and the robot?
- Is the welding equipment easy to maintain?
- Is the equipment 'footprint' important to save floor space?
- Is the level of process equipment integration into the robot system important?

The welding equipment in a robot application is the most critical and sensitive part of the robot system, as this is a continuous process for joining the two metal parts together. It is also the part of the system that normally causes most of the production disturbances in terms of quality problems and down-time in the robot production system.

It is therefore very important to select reliable and high-performance welding equipment to secure the best possible utilisation of the complete robot investment. The welding equipment often represents less then 10% of the total robot investment, but could easily affect the return of the total robot investment in both negative and positive ways by more then 50%.

Welding equipment integration

There are different integration levels available on the arc welding robotic market. From a communication point of view these different integration levels can be divided into the following three main solutions:

1. Discrete I/O-based digital and analogue communication.
2. Field bus communication (can-bus, device net, etc.) using pre-defined schedules or jobs.
3. Field bus fully integrated communication for all arc welding parameters.

1. Discrete I/O-based communication only uses digital and analogue signals and is normally used to control thyristor or non-synergic inverter power sources. This solution normally gives the user the following main programming features in the robot system to control the welding equipment:

- Power and wire feed 'on and off'.
- Changing wire-feed speed output using analogue reference values.
- Changing arc voltage output using analogue reference values.

- Other parameters such as welding speed, voltage and wire-feed speed override, etc. are separately controlled by the robot system in this solution.

Advantage

Simple process interface that can be used by all arc welding robot suppliers and system integrators, as well as by experienced customers.

Disadvantages

Limited functionality to control and syncronise the process together with the robot system. No exchange of real process parameters information between the process equipment and the robot controller.

2. A field bus-based communication (can-bus, device net, etc.) using pre-defined schedules or jobs is normally used to control synergic inverter power sources. In this solution all information is transferred on single field bus cable between the robot control system and the welding equipment. This type of interface will normally give the user the following main programming features:

- Power and wire-feed ‘On and Off’.
- Changing wire-feed speed output.
- Changing arc voltage output.
- Call for pre-defined schedules or jobs made on a separate power source control panel or on a separate remote control unit connected to the power source.
- Change individual parameters, such as average voltage and wire-feed speed within the pre-defined schedule or job.
- Exchange of real process parameters such as measured voltage, current, wire-feed speed, etc.
- Other parameters such as welding speed, average voltage and wire-feed speed override, etc. are separately controlled by the robot system in this solution.

Advantages

Rather simple process interface that can be delivered by all arc welding robot suppliers and many system integrators. Less sensitive to electrical disturbances. Better overall control and syncronisation of the process than I/O-based systems.

Disadvantages

Settings of schedules or jobs to be used need to be programmed on the power source panel or on a separate remote control unit. Individual pulse parameters

15.15 Programming unit (source: ABB).

such as background current, pulse amplitudes etc., cannot be programmed from the robot control unit.

3. A fully integrated field bus communication (can-bus, device net, etc.) is normally used to control advanced synergic inverter power sources. In this solution all information is transferred on a single field bus cable between the robot control system and the welding equipment. In a fully integrated field bus communication the user has access and can program *all arc welding parameters* available in the power source directly from the robot control unit.

Advantage

All arc welding parameters and robot programming is performed from *one single point* remote robot control unit (Fig. 15.15).

15.5.2 Sensors for arc welding

In some robotic arc welding applications there are needs to identify specific arc welding start and stop positions or to compensate for changes in the welding path due to differences in part tolerances between one product and another. Both searching and tracking of the welding path, as well as gap and volume adaptivity can be performed with most robot systems on the market today. This could be performed using different types of available sensor technologies on the market. It is, however, important to understand that for both sensor integration and functionality the robot system could differ considerably between different suppliers.

There are many different arc welding sensors available for robotic applications. Arc welding sensors can be divided into three main types:

- Seam finding sensors
- Seam tracking and adaptive sensors
- Seam inspection sensors

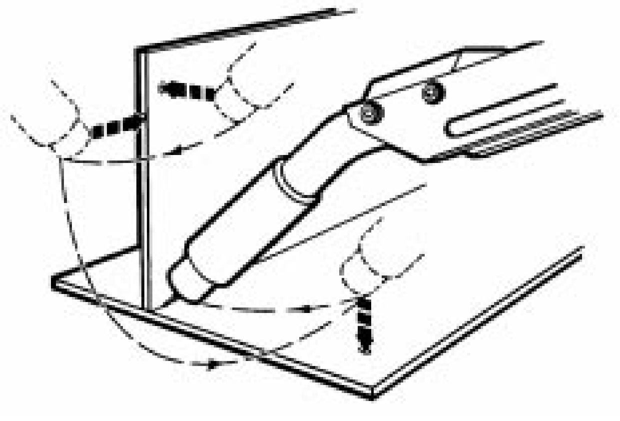
Seam finding sensors

Seam finding sensors can be based on different technologies, such as:

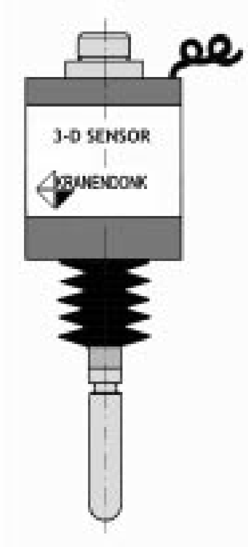
- Touch sensing using electrical contact, between gas nozzle or welding wire (Fig. 15.16)
- Tactile touch sensing using mechanical contact (Fig. 15.17)
- Non-touch sensing using an optical laser beam (Fig. 15.18)

Advantages

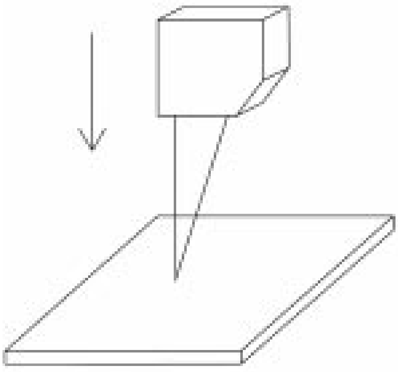
Touch sensors of electrical, mechanical or optical types are quite easy to use and can be implemented for many different welding applications. The advantage with an electrical contact sensor, is that it does not take any extra space in the area of the welding torch. The advantage with a mechanical contact or laser beam sensor, is that they can be used on more or less all types of materials, with or without primer.



15.16 Electrical contact sensor.



15.17 Mechanical contact sensor.



15.18 Laser beam sensor.

Disadvantage

All seam finding sensors will add time to the robot production cycle, some more, some less. The electrical contact sensor types are often sensitive to rust, oxides from milling, grease and primer which can result in detection errors. Both the mechanical and optical sensors need space around the welding torch, which often gives accessibility problems.

Seam tracking and adaptive sensors

Seam tracking sensors can be based on different principles such as:

- 'Through the arc' tracking using measurements from the welding arc parameter itself.
- Optical laser tracking system using a laser light stripe, or a linear or circular scanning laser beam.
- Camera vision tracking using a structured light image camera.

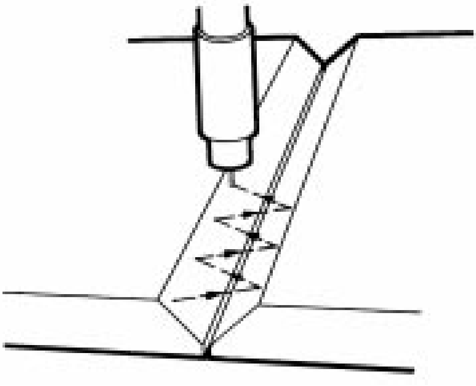
Through-the-arc sensor systems

A 'through-the-arc' sensor system (Fig. 15.19) is designed to identify the variations in joint position in relation to the programmed path. This may be caused by inaccuracies in the details to be welded or in the fixation of the components. The sensor will automatically monitor and track the weld joint during welding. The measurement principle differs between the suppliers, but the main idea is the detection of the variations in current and voltage (impedance) when the robot is weaving the torch across the seam. The data are recorded in real time and analysed by the robot sensor system which then will result in robot path adjustments to ensure that the arc stays in the weld joint along the entire weld path.

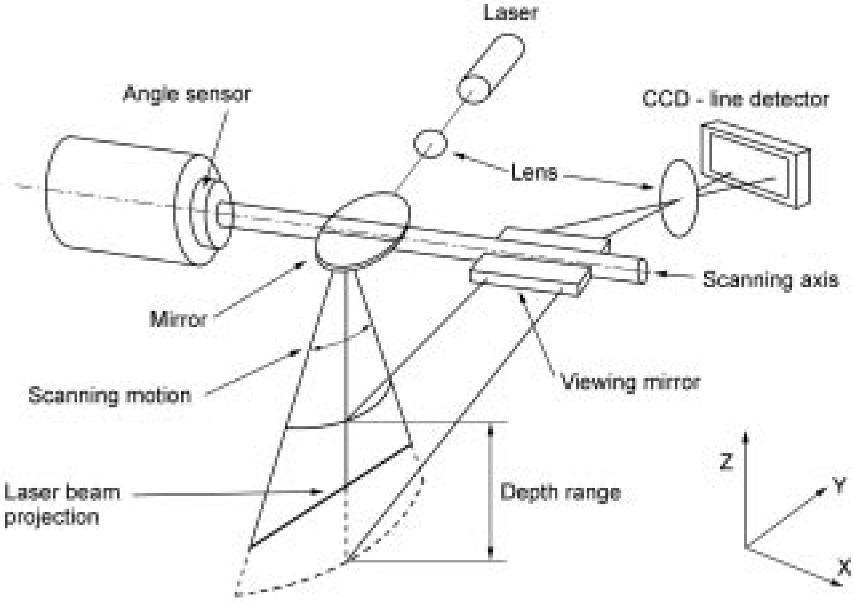
Optical laser and camera vision systems

A laser-based optical or a camera vision device is mounted in front of the welding torch to monitor its position (see Figs 15.20 and 15.21). It controls the movement of the welding robot directly through a digital interface.

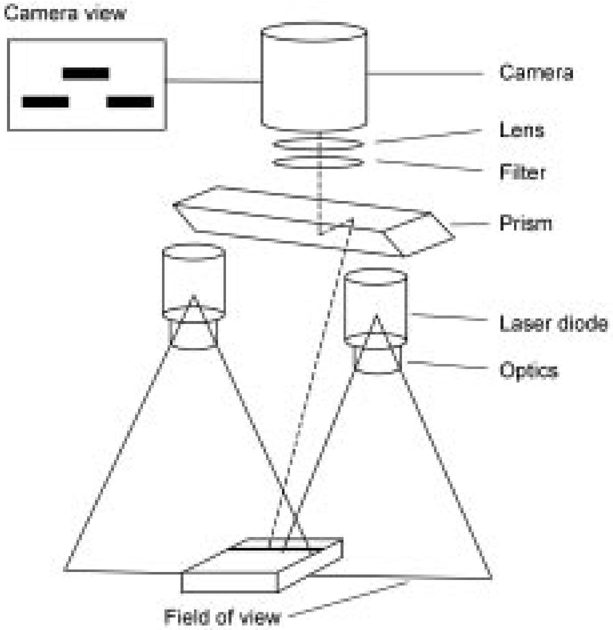
Real-time joint tracking performed by the sensor first detects the position of the joint and then guides the welding robot, during welding. The sensor communicates with the robot and sends the trajectory corrections for maintaining the tool centre point at the optimum position in the joint.



15.19 'Through the arc' tracking, using weaving.



15.20 Optical scanning laser tracking system.



15.21 Camera vision tracking system.

Most of these systems can also measure gap and shape of the joint and calculate the cross seam area to be used for adaptive welding due to joint variation along the weld path.

Seam inspection sensors

Different 'brands' of seam finding and tracking systems

All the main arc welding robot suppliers have their own 'through the arc' seam tracking systems. However, the specific performance can differ from supplier to supplier and from application to application, so the advice is always to test or verify the performance from case to case.

There are different suppliers of laser seam finding and tracking systems on the market. Here are some of the most common suppliers for robotic welding.

- Servo-Robot Inc.
- Oxford Weld Technology Ltd
- Meta Vision Systems Ltd
- Meta-Scout GmbH

Comparison between different sensor types

The advantage of a 'through-the-arc' sensor is that it does not take any extra space in the area of the welding torch. 'Through-the-arc' sensors are very useful in heavy welding applications, especially when combined with advanced multilayer software functionality.

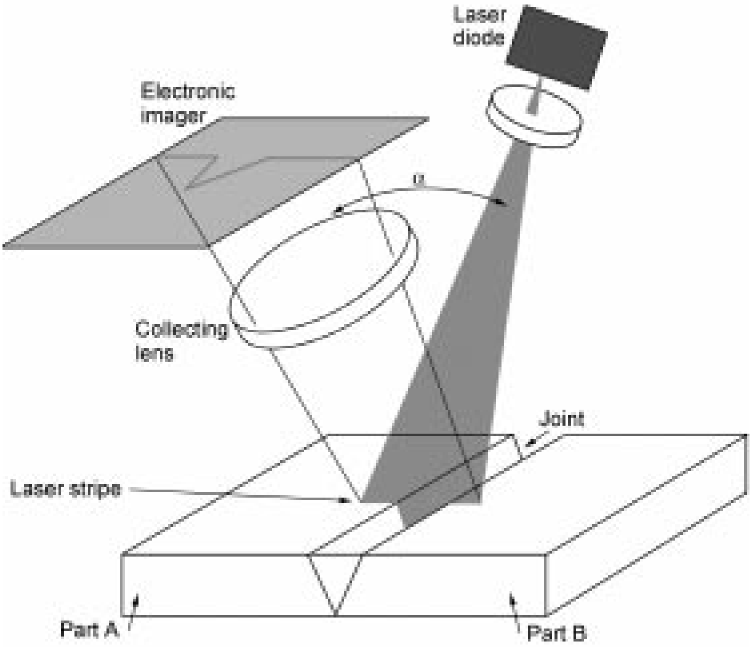
The laser-based optical or camera vision sensors can, in general, be used together with higher welding speed than using 'through-the-arc' sensors. The laser-based and camera vision sensors can also measure the actual joint configuration including gap and shape to be used for adaptive welding as shown in Fig. 15.22.

All seam tracking sensors require higher skilled technicians and operators if compared to a robot system without seam tracking systems. Due to higher system complexity seam tracking system will in most cases influence the overall up-time in the robot system in a negative way.

One of the main disadvantages with a laser-based optical or camera vision sensor is that it takes extra space in the area in front of the welding torch, which can give accessibility problems in some applications.

15.6 Safety systems

The operator and the surrounding environment must be protected from the moving parts in a robot welding station. This is performed by fences or walls around the station. The area within the fences or walls is called the supervised area.



15.22 Laser triangulation for adaptive welding (source: Servo-Robot Inc.).

To avoid risks when entering supervised areas there is continuous supervision of:

- The status of safety components.
- Operator communication.
- Moving machine parts.

This is provided by a safety module for safety supervision, which includes functions to immediately cut the control system's operating stop loop when a course of events occur that can result in personal danger.

Examples of such events are:

- Hardware failure in the safety equipment.
- Incorrect operation.
- Carelessness.
- Machine fault.
- Unauthorised entry.

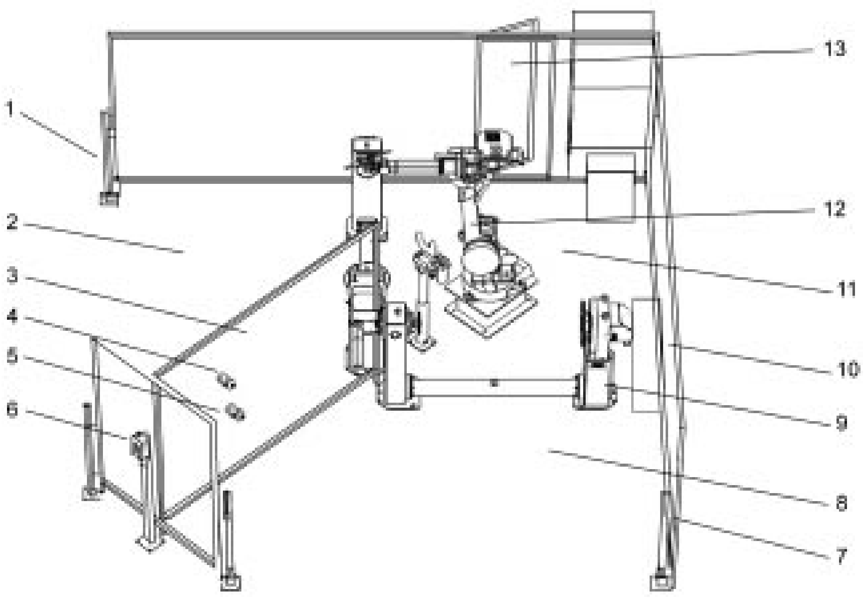
15.6.1 System solution

In addition to the safety module, the safety system consists of different types of sensors and actuators. Their purpose is to check the status of the units within the robot station and receive information from the operator. This information is then transferred to the safety module which evaluates whether the system should be stopped or not.

The way the safety system is designed, with reference to distances between fixed parts and movable parts as well as movable parts and safety units is determined by safety regulations.

Figure 15.23 shows a traditional robot welding station with its safety system and safety components. The following parts are involved:

1. Light barrier, station one
2. Supervised area, station one
3. Barrier
4. Time-reset unit, station one and two
5. Safety activation unit, station one and two
6. Operator panel
7. Light barrier, station two
8. Supervised area, station two
9. Workpiece positioner
10. Barrier
11. Supervised programming area
12. Robot with station indicator on the first axis
13. Interlocked door



15.23 A traditional robot welding station with its safety system and safety components.

Light barriers (1, 7)

The light barrier protects the supervised areas in front of the workpiece positioner. If the light beam is broken in the station where the robot is active, the system will shut down.

There are different types of light barriers, light beams usually with three beams or light curtains with a number of beams close together. The distance between the light barrier and the workpiece, positioner or robot is determined by the stopping time and international/local safety regulations.

Light barriers are relatively sensitive and have to be protected against mechanical impacts.

A more sturdy solution is the floor scanner. It scans the protected area in front of the workpiece positioner. If someone enters the scanned area the system will shut down. Another advantage with a floor scanner is that it is a neater system solution with less cabling compared to light barriers.

Operator panel (6)

The operator panel is the operator interface to the station where the operator starts and stops the station. It usually consists of push buttons for 'Start Cycle', 'Stop Cycle', 'Emergency Stop', etc.

Station indicator (12)

The station indicator activates the light barriers and the workpiece positioners. When the robot is in the position shown in the figure, the light barrier and the workpiece positioner at station one are activated and entrance is not permitted. Station two is free to enter for unloading and loading a new workpiece. When the robot is ready and leaving station one, after a command from the operator panel, the light barrier and the workpiece positioner at station one are de-activated and at station two they are activated. The border for switching between the two stations is located at the safety barrier (3).

The station indicator consists of an electrical switch mounted on the first axis of the robot.

Time-reset unit (4)

The purpose of the time-reset unit is to prevent starting of the station if someone presses the push button 'Start Cycle' on the operator panel while the operator is within the protected area at unloading or loading the fixture.

The time-reset unit consists of a push button with a timer which activates the safety system within a certain time (approximately 10 seconds). The following example describes how it works.

- Loading of the fixture is finished and the operator presses the push button on the time-reset unit.
- The operator then has about 10 seconds to leave the supervised area and press ‘Start Cycle’ on the operator panel.
- If it is done within the set time, the safety system is activated and the next cycle starts.
- If it is not done within the set time, the safety system will not be activated and it will not be possible to start the station.

Sometimes there is a horizontal light curtain supervising the area in front of the positioner, which replaces the time-reset unit.

Interlocked door (13)

The interlocked door protects the supervised area around the robot. It works as follows.

In production mode

If someone opens the door while the robot system is in production, it is immediately switched to the off state. A restart is made by closing the door and resetting the safety system. The reset is usually made by pressing the ‘motors on’ push button on the robot control cabinet and then by pressing the ‘Start Cycle’ on the operators panel to start the station again.

In programming mode

The robot system has to be switched over to programming mode. The programmer opens the interlocked door and enters the supervised area around the robot. By closing the door and resetting the safety system, which is done from the teach pendant, it is possible to start the programming. In programming mode the maximum speed of the robot is reduced to 250mm/sec and the positioner speed is reduced to 10% of maximum speed.

Safety activation unit (5)

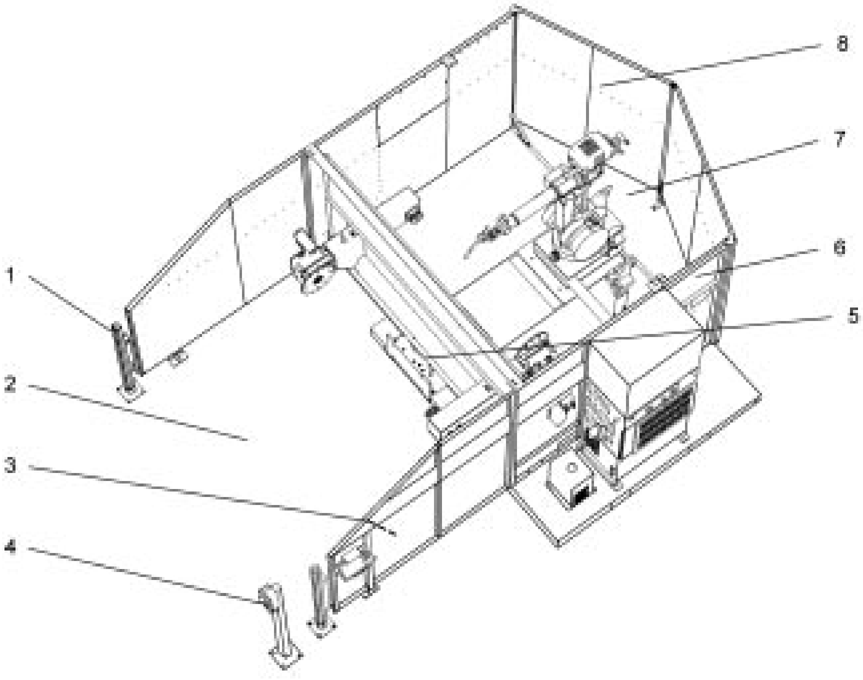
Sometimes it is necessary to do the programming of the workpiece in the supervised area in front of the positioner. In programming mode the safety system is activated, i.e. the robot and positioner are powered up.

When the programmer has passed the light beams and entered the supervised area, the safety system must be reset. By pressing a push button on the safety activation unit, the programmer confirms that he has passed the light beam and the safety system can be reset from the robot programming unit.

15.6.2 System solution for a welding station with station interchange

In a robot welding station using a positioner with station interchange (Fig. 15.24), the safety system is simpler since only one area has to be supervised. Only one light barrier and time-reset unit is required and the safety activation unit is not required at all because programming can only take place in the supervised programming area. A station indicator mounted in the positioner's station interchange unit ensure that the motors on the supervised area always are de-activated. The following parts are involved:

1. Light barrier
2. Supervised area
3. Time-reset unit
4. Operator panel
5. Workpiece positioner
6. Interlocked door
7. Supervised programming area
8. Barrier



15.24 A robot welding station using a positioner with station interchange.

When the cycle time is short and the operator has to load and unload the station very frequently, or where there are demands of a small station footprint, it is better to replace the light barriers with mechanically operated barriers.

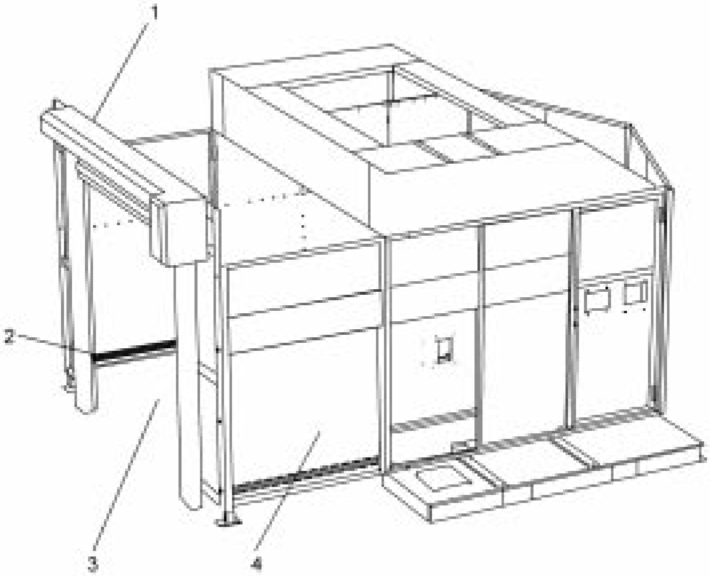
Examples of mechanical barriers are:

- Roller doors
- Sliding doors
- Hatches

The mechanical barriers can be manually operated, driven by electrical motors or by pneumatic cylinders. Because they are a part of the safety system they are equipped with sensors which supervise whether they are open or closed.

When the mechanically operated barrier is closed it physically prevents anyone entering the supervised area and reduces the distance between the moving machine part and barrier. The distance is only for the robot and workpiece positioner working envelope. A horizontal floor-mounted light curtain prevents the risk of someone becoming trapped in the supervised area behind the mechanically operated barriers and moving machine parts. Figure 15.25 shows a robot welding station equipped with a roller door.

1. Roller door
2. Light curtain
3. Supervised area
4. Barrier



15.25 A robot welding station equipped with a roller door.

15.6.3 Summary

The safety system must be adapted to the individual production situation but the solutions described are examples of solutions used in practice. Different robot station suppliers may suggest alternative solutions depending on their experience from installations. The main goal is always to get a safe way of using the robot station.

15.7 Offline software tools

Offline PC-based software for robotic welding is a very important tool for simulating, implementing and optimising robot station solutions and robot programming. Offline programming software allows robot programming to be done on a PC in the office without shutting down production. The following main advantages can be achieved with good offline software:

- Risk reduction in programming and production
- Quicker start-up
- Shorter change-over
- Increased productivity

There are mainly three types of offline software tools available on the market for robotic arc welding:

- Parameterised macro-based offline programming software.
- 3D offline simulation/programming software.
- MIG/MAG process simulation tools.

15.7.1 Parametrical macro-based offline software

These software tools are mainly used for one-piece production in shipyards, construction and off-shore production and when the product can be described with numerical data and formulae. One example is a software tool called ARAC (Arithmetic Robot Application Control from Kranendonk Production System BV).

This type of software system can be used to create ‘first-time-right’ programs that require no manual tuning. Besides programming it can be used for online editing of process parameters for welding and/or cutting processes.

15.7.2 3D offline simulation/programming software

These software tools are mainly used for simulation and programming of robots for volume-produced parts. There are many different types of 3D offline PC software tools available on the market for robot arc welding. Many of the main


VirtualArc®
Robotic MIG/MAG
Weld Tuning
Mild Steel Edition
ABB
Copyright 2003, ABB Automation Technologies AB, All Rights Reserved
Load
New
Delete
Exit
(a)
System parameters
Application
Process parameters
Pre-weld analysis
Economy
Report
3.00 mm
3.85 mm
3.00 mm
System Voltage
System Current
Analyse
Dimensions
Display working range / Default values
Synergic setting V
Process mode
Shielding gas
Gap
W diam
WS
WFS
TA
ABB
(b)

15.26

arc welding robot suppliers have their own 3D offline software tools which are designed for their own robot and product portfolio, e.g.:

• RobotStudio with ArcWeld PowerPack	Supplier: ABB
• MotoSim	Supplier: Motoman, Yaskawa
• FanucWorks	Supplier: Fanuc
• DTP 2	Supplier: Panasonic

There are also independent suppliers of 3D offline PC simulation/programming software, e.g.

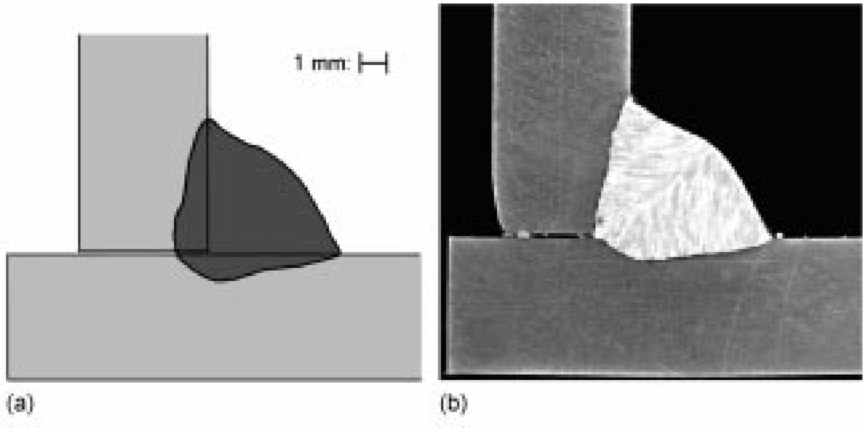
• eM-workplace (RobCad)	Supplier: Technomatix
• IGRIP® with UltraArc	Supplier: Delmia

The differences in functionality and performance can be significant between these tools. It is important to make a comparative study before selecting product and supplier. Examples of problems that have to be looked into are:

- Is it possible to make a direct download of an arc welding offline program to the robot controller without the need for fine-tuning in a later stage in the online system?
- Is the offline software object-oriented using reference coordinate systems?
- Is the offline-produced program the same as in the robot controller, or is program language conversion needed?

15.7.3 MIG/MAG process simulation software tools

These software tools are new offline tools that have recently been available on the market. As 50–90% of the total arc welding robot cycle time is arc time it



15.27

will become more important that the MIG/MAG process can also be simulated and programmed in an offline environment.

An example of this type of software is VirtualArc (ABB) (Fig. 15.26). VirtualArc® offers robot programmers, operators and welding engineers an expert system with deep arc welding process know-how. This in turn gives the possibility to improve process control, final welding quality and productivity. The simulation tool includes the state of the art of the information needed for prediction of the MIG welding process. The software offers a user-friendly interface, minimising the process implementation time and costs of robotic MIG welding.

The results from the predictions using the VirtualArc software shows that the simulated weld profile is very close to the real weld profile (Fig. 15.27(a) and (b)).

16

Optimising the use of robotic MIG welding

R GUDMUNDSON, Air Liquide Gas AB, Sweden

16.1 Introduction

MIG welding is used both in manual and automatic operations. Automation includes equipment especially built for specific workpieces or groups of workpieces as well as robotised solutions. The use of robots is increasing since the flexibility of the movement and the programming means that it is easy to adapt the equipment to new objects. The standardised robotic solutions are in most cases also much cheaper than the purpose-built solutions. For automatic welding the reliability of the welding process and the equipment must be very high. In manual welding the welder controls the process and has different means to correct the discrepancies that may appear. All these controls must be taken into account in automation either by actions before the welding or during the process.

The advantages of robotic welding are:

- High productivity mainly due to increased arc time and higher welding speeds.
- More consistent weld quality and often also better quality than for manual welding.
- Better working conditions.
- In many cases lack of well-trained manual welders.
- A more efficient organisation formed around the robot station.

The limitations may be:

- Higher demands on design.
- Need of more accurate preparation of the parts to be welded and the fixtures.
- Better stability of the process and the equipment compared to manual welding.
- A need of more knowledge in the workshop about programming and service of robots.

In this chapter some important points to overcome these problems are discussed. These general aspects are followed by applications from sheet metal production in the automotive industry and from heavy steel production of wheel loaders with long welding times in the robot station.

16.2 The welding process

The dominating welding method for robotic welding is MIG welding. MIG welding has the advantage of having automatic feeding of filler material and shielding gas, high stability and controllability of the process and equipment as well as good tolerance towards variations in gap and position.

Unalloyed steel is the most frequently used material but aluminium alloys and stainless steel are also prevalent. For lower thickness, solid wires are most often used. Both solid wires and flux-cored wires are used in heavier thickness. Metal-cored electrodes give high deposition rates with good welding quality. In order to increase the productivity new processes based on a single wire or two wires (tandem or twin) are introduced. The most recent development is the combination of MIG welding with laser welding called laser hybrid welding.

The welding process must have a tolerance box that is large enough. This means that the parameter values chosen can give an acceptable quality in spite of the variations that appear in position of the joint, gap width, stick-out, etc. It is therefore more suitable to use safe parameters instead of parameters that give the maximum welding speed. Downtime due to quality problems always tends to be very expensive.

16.3 The design of the workpiece

The objects that are welded in robot stations are normally high series products. Simpler programming and cheaper fixtures means that smaller series will be more economical to weld with the robot. Offline programming of the robots has given new possibilities to decrease programming time and increase the production time in the robot. Some general aspects of design of objects to be welded by robots are:

- Few parts and components in the workpiece means easier programming, simpler fixtures, easier handling and storage.
- Standardisation is advantageous. If possible few material thicknesses and material qualities should be used. This means easier programming and testing of welding parameters as well as smaller storage of material.
- The parts should be easy to store, easy to separate and identify, e.g. by special identification in the design.
- The parts should also be easy to load and unload from the fixture.
- Variants, product families and modularised design can be used to increase the series of objects in the robot station and facilitate the changeover between different objects in the station. Similar design means minor changes in fixtures

used, in welding parameters, storage of parts, etc. Through parametric design, i.e. similar products with the same main design but only changes in certain dimensions it is also possible to facilitate the programming.

In the first generation of robots the objects for welding were fairly small but now very big objects are also welded with welding times of many hours for a single object. One example is the use of robots in shipyards for welding in the hull structure. Both tack welding and final welding of the joints can be robotised.

The workpiece must already be adapted to robotic welding in the design stage. The joint configurations shall be evaluated as well as the tolerances of the parts to be welded. Joint preparation methods with sufficient accuracy must be chosen. The next step is to assure the positioning of the joints and control of the gaps. This can be made by tack welding and/or by fixtures. Fixturing in the object itself is also possible by special design of the parts. Analysis of the deformations during welding is important in order to find the right welding sequence. The deformations are not only important for the final shape of the objects but also for the accuracy needed for robotic welding. Sometimes the welds can be made as intermittent welds to decrease the amount of weld metal and the deformation of the parts.

16.3.1 Joint configurations

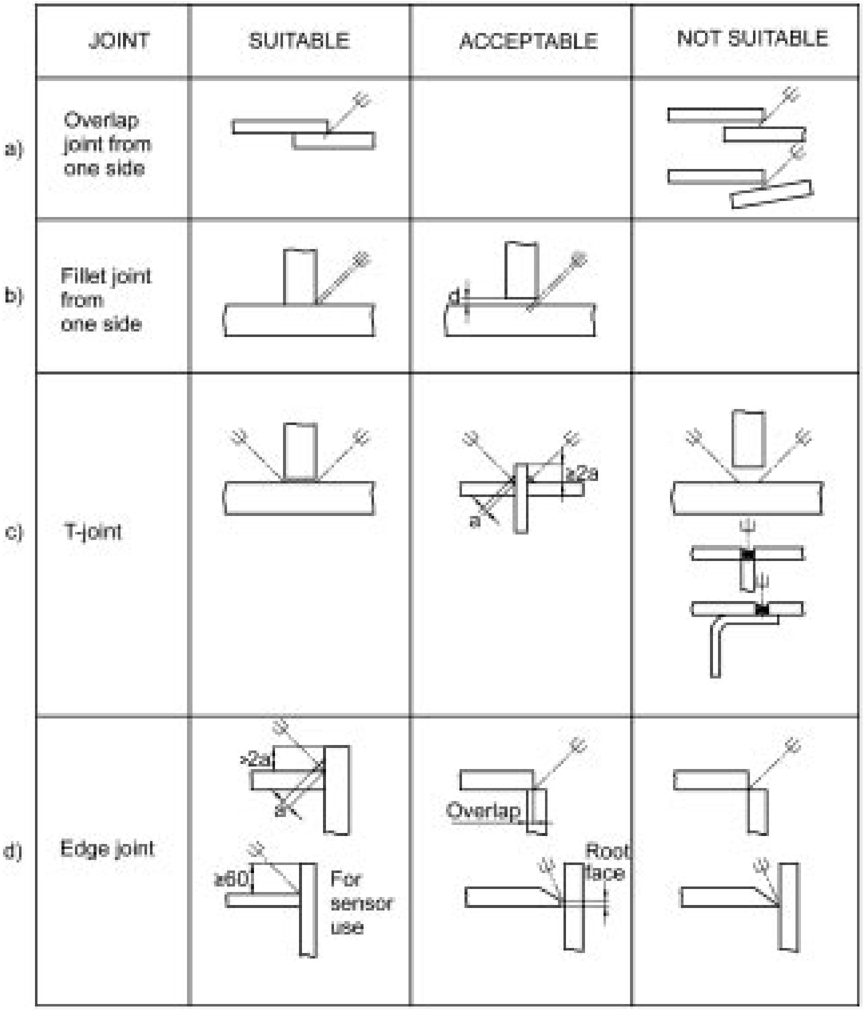
An overview of different joints and their suitability for robotic and automatic welding is given in Fig. 16.1. It is most often preferred that it should be possible to weld the workpiece from the upper side only. Welding on two sides needs an unloading/reloading sequence and double fixtures. In many cases, especially for small objects in thin sheet, it is also more convenient if the welding can be done with limited changing of the position of the object with the positioner since this normally increases cycle time.

Fillet and overlap joints are most common for robotic welding. There is always material below the arc and the risk of burn-through is limited. The positioning of the upper part must be fixed but the lower one can be allowed to move somewhat and compensate for variations in the dimensions of the parts.

For overlap joints in sheet thickness below 3 mm in steel it is preferred to have the thinnest sheet in the upper part if possible. In aluminum the opposite is preferred.

The fillet joint may have a disadvantage compared to the overlap configuration. The arc may deflect against one of the joint faces if it is not correctly positioned. The same is also true for V-joints.

For butt joints a backing is preferred, either as an integrated part of the design or put there only to improve the weldability. The requirements for positioning and for joint tolerances are also smaller than for joints with open roots. For butt joints where full penetration is not required a zero gap is preferred.

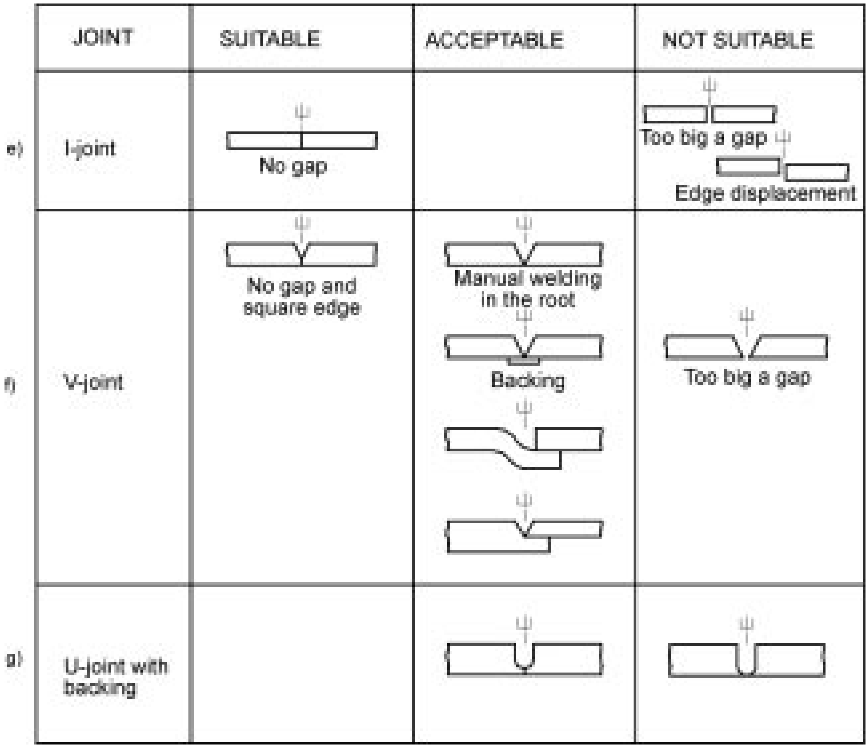


16.1 Joint configurations for automatic and robotic welding.

The corner joints and butt joints with open roots in thin sheet are not the most suitable ones since the preparation and assembly of the parts often gives gaps along the joint. Varying gaps are difficult for a robot to weld.

16.3.2 Tolerances of the parts and assembly

The parts of the workpiece must have good tolerances. This influences the cutting and joint preparation methods to be chosen. The fixtures must also be very accurate. A general rule is that the joint should not be more than about 0.5 mm from the programmed position of the robot. This is about the same for thin



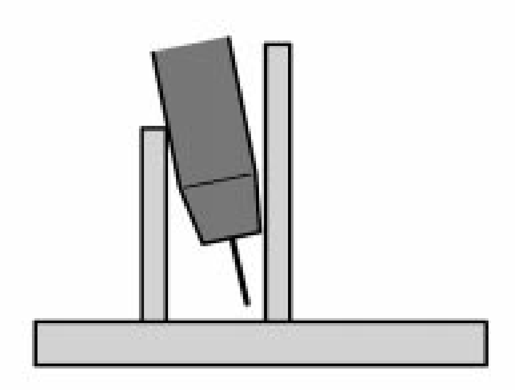
16.1 (continued)

and thick material. The stiffness of the arc is higher at high currents but the arc length is also bigger and the arc can deflect to the nearest joint face if the welding gun is not correctly positioned. This leads very easily to lack of fusion.

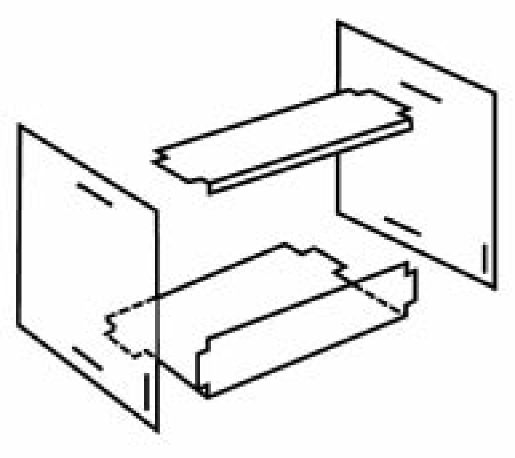
16.3.3 Accessibility

The welding gun as well as other parts handled by the robot arm limits the possibility to reach the joint. It is also necessary to have a certain angle between the welding gun and the joint both along and transverse to the joint. This can be solved by the degrees of freedom of the robot and manipulating systems. This is not enough but must also be taken into consideration in the design phase. It is preferred to have as open structures as possible. Narrow distances between different plates may cause difficulties to reach the welds and need to be avoided, see Fig. 16.2.

It is not only the object but also the fixtures that limit the working position of the welding head. Instead of using complicated fixtures the design of the parts and objects can be adapted by using taps and holes in the parts, special indentations in one of the parts, etc. If the fixing of the parts is done in the object



16.2 The importance of good accessibility for the welding gun.



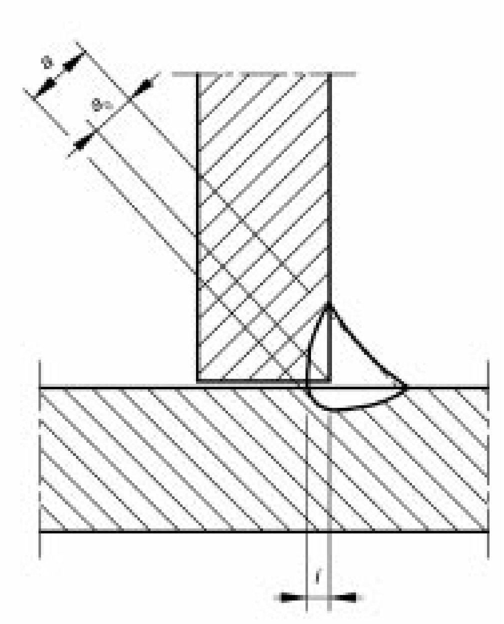
16.3 Special design to facilitate fixing of the parts.

itself a simpler fixture can be used. One example is shown in Fig. 16.3. The accuracy of the parts must be high. Laser cutting has offered this new possibility in many cases. The angle between the parts must be 90º. Similar solutions are possible in parts made by punching.

Modern offline simulation systems make it possible to adapt the design of objects and fixtures to robotic welding at an early stage of the design phase.

16.3.4 Weld metal optimisation

Deformation is caused by the local heating of the object during welding. The drawback of deformation in this case is that the positions of the joints can change during the welding cycle and lead to weld discontinuities. Stable fixtures



16.4 Deep penetration can be used to lower the weld size in fillet welding. Nominal throat thickness a_o, achieved throat thickness *a* and side penetration *i*. Normally only part of the penetration *i* can be used in the strength calculation.

reduce the problem but another solution is to decrease the amount of weld metal. Optimised throat thickness is one possibility. The amount of weld metal should always be kept to a minimum. Compared to manual welding it is easier to get the right size of the welds all the time.

For heavier material the throat thickness can be lowered if penetration into the fillet weld can be used in the strength calculation (see Fig. 16.4). The control of the penetration is more stringent in robotic welding compared to manual welding due to the control of the whole process. It may also give the possibility for the production to use one single pass instead of three passes for a fillet weld.

Intermittent welding instead of full welding is possible if the fatigue loads are not important. The starts and stops of the welds are especially dangerous for the initiation of fatigue cracks. The length of the intermittent weld should be at most about 50 mm.

16.4 The preparation of the parts and assembly before welding

The preparation of the parts includes different cutting methods, e.g. shearing, punching, nibbling, gas cutting, plasma cutting, laser cutting, abrasive water cutting. After cutting, the parts are often formed in a plastic forming operation.

The parts are then assembled in fixtures for final welding. Often the parts are tack welded to assure the dimensions and to have the right position of the objects during final welding.

16.4.1 Cutting methods

The dimensional tolerances and the geometry of the joint faces of the parts depend on the cutting method used. It is therefore important to choose the method that gives the right quality needed for robotic welding. Some general comments can be given.

The thermal cutting methods have the disadvantage that thermal effects can give cuts that are not perfectly straight. Different methods can improve the situation, one of which is the use of parallel cuts with two burners. Lower heat input with laser cutting compared to gas and plasma is advantageous. A perfectly square cut is easier to achieve with laser than with plasma but new high definition fine-plasma cutting methods have improved this situation. A rough guide says that the dimensional tolerance for laser is $\pm 0.1 - 0.2$ mm, for plasma $\pm 1 - 2$ mm, fine-plasma $\pm 0.2 - 0.4$ mm and gas cutting $\pm 1 - 3$ mm. These figures have to be checked in the actual equipment.

Punching and nibbling (repetitive punching) introduces no heat but the cut will have markings from the punch. The water-jet cutting gives no heat but is a relatively slow process. For metals it is used mainly for aluminium and stainless steels in thicknesses where other methods are not suitable.

Sometimes there is need for V- or Y-joint preparations. Mechanical cutting or milling gives the best result. Manual thermal cutting or grinding is normally insufficient.

In the end it is important to evaluate the quality very thoroughly because the success of robotic welding is dependent on the quality of the parts to be welded.

16.4.2 Forming

Forming of thin sheet is often done by deep-drawing which normally gives a high accuracy owing to the high deformation put into the material during the process.

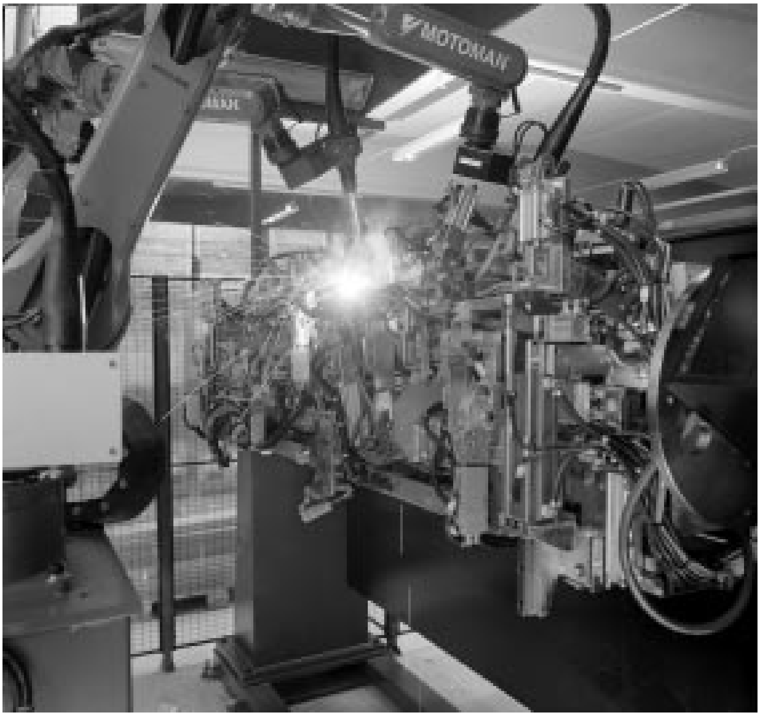
Plates of heavier thickness are often bent in presses. This can lead to variations in the bending angle caused by varying thickness, varying strength of the plate and the springback of the plate. This means that the gaps between the parts may vary and make welding more difficult. Modern types of press can compensate for these problems.

The surface of the objects must be clean enough to avoid disturbances in the process. A small amount of oil can be acceptable on steel. Zinc-coated steel is normally used in the automotive industry but not more than $10\,\mu$m thickness. Higher thickness will give a lot of spatter and also is often a cleaning problem for the welding gun. In heavy thickness steel the surface condition from hot rolling can be accepted but sandblasted material is preferred. For aluminium welding the surface must be very clean, otherwise pores can appear in the weld.

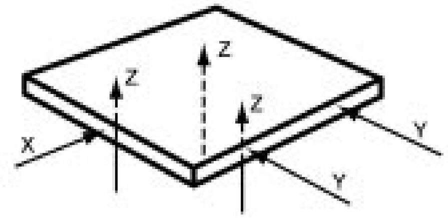
16.4.3 Assembly

The robot cooperates with the positioner moving the fixture and its workpiece to the right welding position (see Fig. 16.5). Fixtures are needed to accurately position the joint. They must have sufficient stability to withstand the heat from the welding and prevent the deformation that appears. It must also withstand unwanted deformations from the robot if it moves wrongly and touches the fixture. The dimensional accuracy is dependent on the way the fixtures are designed. The 3-2-1 principle is used which means that 3 support points are fixed in the Z-plane, 2 in the Y-plane and 1 in the X-plane to get the fully defined position (see Fig. 16.6). The accessibility for the welding must also be good. In some cases there is one fixture for fixing the parts by tack welding and another fixture for the final welding. This last fixture can be made more open.

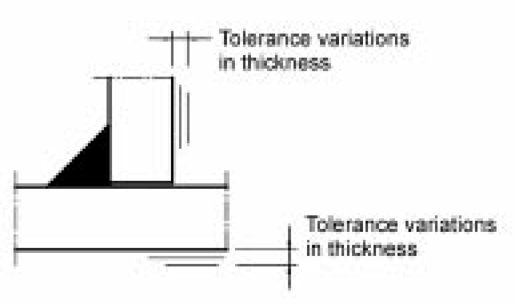
The tolerances of the sheet and plate thickness may influence the position of the joint. In order to avoid this as much as possible it is important to have



16.5 Cooperation between two robots and one positioner.



16.6 Six support points give a fully defined position.



16.7 Elimination of the influence of plate thickness variations in fixture design by locating the support points of the fixture at the same sides as the welds.

already taken it into consideration already in the fixture design. An example is shown in Fig. 16.7.

The tack welding prevents the parts from moving depending on thermal dilatation during welding. It can be done manually or by the robot before the final welding. The location of the tacks is important and may influence the final weld quality. When welding over a tack weld there will often be a defect that is dangerous in fatigue loading. If possible the tacks should be located in non-loaded positions to minimise the risk of fatigue cracks.

16.5 Equipment, filler materials and shielding gas

The equipment used in robotic welding must be designed to have very high reliability. This is also true for the feeding of filler material and for the supply of the shielding gas.

16.5.1 Equipment

The stability of the power source must be good which means that the parameters are kept constant regardless of variations in the main supply or internal heating. It must have enough capacity taking into consideration the high duty cycle in the robot station.

The wire feeder should be feedback-controlled to keep the wire-feed rate constant even if the motor is warm, the robot arm bends the hose package or the feeding resistance increases for some reason. Tandem wheels are preferred since this gives a safer feeding without increasing the pressure on the wheels possibly leading to a deformed electrode. This is especially important in aluminium welding. A push–pull system can also be used in this case.

The hose package must be flexible and must withstand complicated movements in order to reach all the welds. The same is the case for the welding gun but it must also be robust. There are always risks of collisions between the object and the workpiece, for example during programming. The water-cooling system for water-cooled guns must be leak-proof otherwise there could be pores in the weld especially for aluminium.

A cleaning station is needed to clean the gas nozzle from spatter. This can be done either by a milling device or by air blasting. The frequency of this operation is dependent on the process and the material. Coated steel requires more cleaning.

The length of the contact tube depends on the cast of the electrode. A long contact tube is more suitable if the cast of the electrode is small. The mechanical wear will be bigger if the cast is bigger. A short contact tube and a small cast gives an unstable arc and electrically induced wear due to sparking. The most favourable solution is if the outgoing hole of the nozzle is intact and that the current is transferred near the exit hole. The hole must also be in the centre of the nozzle. When changing contact nozzle the position of the electrode will otherwise change.

Other equipment that can be used in the robot station to increase the reliability is a cutting station that cuts the electrode before starting to improve the arc ignition and a TCP (tool centre point) station to check the position of the electrode.

16.5.2 Filler material

In robotic welding the current transfer in the contact tube is a decisive factor for the process stability. The cast and helix of the electrode are important but also the surface condition of the electrode. A thin copper layer is normally used for massive electrodes to improve the contact in the contact tube and to decrease the wear of the contact tube. The copper coating is also possible for flux-cored electrodes with a closed cross-section. Other types of flux-cored electrodes that are only folded cannot have a coating since the coating is applied electrolytically. The electrolyte may penetrate into the flux.

The bobbins used in manual welding are also used in robotic welding. The winding must be accurate to avoid dewinding problems. In order to decrease the time for changing bobbins special big packings are used.

16.5.3 Shielding gas

The gas flow must be monitored regularly and an alarm is convenient if the gas flow fails.

For the choice of shielding gas the most important parameters are the thickness of the sheet, the coating of the parts, the desired appearance and the accepted spatter. High argon content gives a smooth surface of the weld and a low amount of spatter. With more CO_2 the penetration increases and the bead appearance will be rougher. For zinc-coated material more addition of CO_2 improves the cleaning of the base metal.

The shielding gas for welding with flux-cored electrodes should always follow the recommendations from the suppliers.

16.6 Welding process and programming

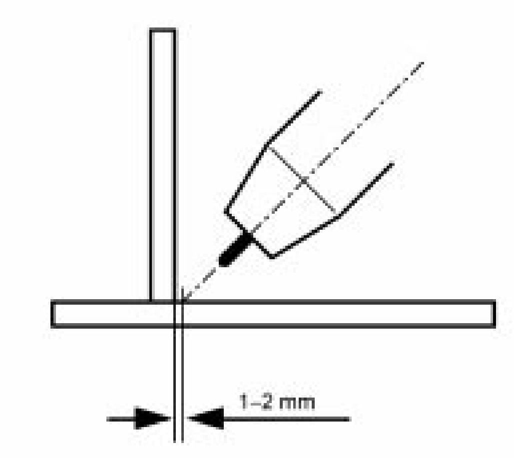
The welding process parameters and the programming both influence the productivity, the quality and the reliability of the process.

The productivity is measured by the cycle time in the robot. The cycle time comprises the time for movement of the robot and the equipment, e.g. the positioner and the arc. The movements of the robot can be very fast since it is fairly light. On the other hand, the other equipment can be slower. A combination of movement of a positioner and simultaneous welding is an effective solution. The welding speed should be as high as possible. To get good reliability at the same time it is not suitable to use the highest speed but to weld a little more slowly. This means fewer stops and welding discontinuities.

The welding sequence is important to minimise the deformation. It could be better to weld first on one side rather than on the other. The drawback is the increased cycle time.

General aspects on quality have already been discussed in earlier chapters. Some comments regarding robotic welding are given below:

- The fixing of the objects is more important than in manual welding. Since the arc deflects easily towards the nearest plate surface and can give a lack of fusion accurate programming is important. The contact tube distance must be kept constant during programming otherwise the welding parameters will change during welding.
- An example of positioning for fillet welding is shown in Fig. 16.8. The right position is from 0.5 to 1.0 mm out from the joint on the base plate when welding in the horizontal position.
- In the automobile industry, steels with coatings of zinc, aluminium or mixtures are often used to prevent corrosion. These materials are more difficult to weld than normal steels. With a coating thickness of 10 μm zinc welding is possible but 30% slower than for uncoated steel. A coating



16.8 Offset in programming of horizontal fillet welds.

thickness of 25 μm produces an unacceptable amount of spatter. A coating of 20 μm of aluminium gives the same problems as 10 μm of zinc. The procedure for welding with coating is to burn the coating and release the gases before the melted material reaches the coating. A small gap between the sheets is advantageous in overlap joints in order to let the gases leave and avoid pore formation.

17

Automotive applications of robotic MIG welding

R GUDMUNDSON, Air Liquide Gas AB, Sweden

17.1 Introduction

Robotic MIG welding is used extensively in automotive production for parts and for car bodies on the main production line. In both cases there is a high demand for quality and reliability as well as productivity. Two cases studies are presented below – welding of a rear support arm and welding car bodies on the main production line.

17.2 Rear support arm

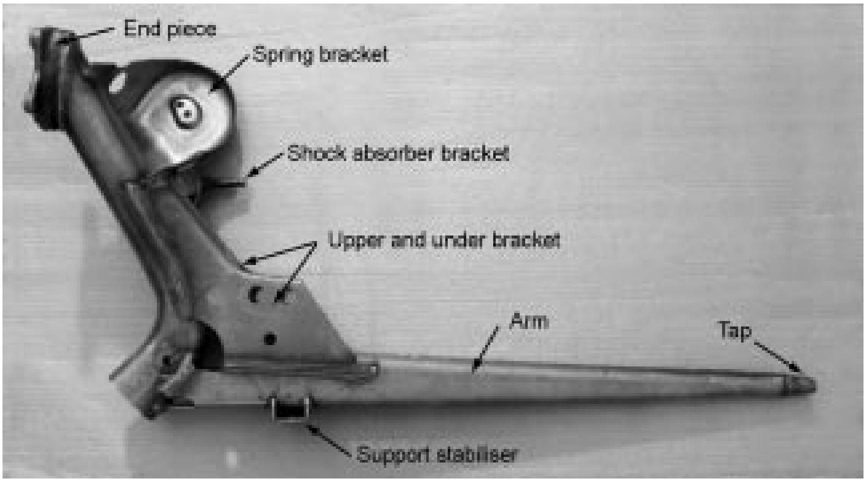
The rear support arm for a car is welded in a robot line. There is one robot line for the left and one for the right support arm. Figure 17.1 shows the left support arm. The rear wheels are screwed into the end piece with four bolts. The support arm acts together with a spring to transfer the weight of the car body to the wheels and the shock absorber, which prevents fast oscillations of the body when driving on roads of bad quality. The object is heavily loaded in fatigue.

The steel sheet has a thickness of 2.5 to 3 mm, but the end piece has a thickness of 11 mm in normal conditions but 36 mm in a model with 50 mm wider wheelbase. The total length of the welds is 3.0 m.

The series is 200,000 pieces per year with a maximum capacity in the robot line of 6000 support arms per week.

17.2.1 The welding sequence

The support arm is welded in three stations. In the first, the butt weld on the arm and overlap weld on the tap are welded by one robot. In the second, one robot welds part of the spring bracket and support stabiliser. In the third, with two robots the welding is finalised. The loading and unloading in the first station is fully automatic. The pieces are fed from a magazine and the welded parts are transferred to a rack that is automatically changed when filled. The second station is manually operated. Both loading and unloading of the fixture are done



17.1 Left support arm.

by one operator. The final complete welding station is also manually operated. The operator loads the support arm, the spring bracket, the upper and lower bracket and shock absorber bracket in the fixture. The reason for the manual operation of the two stations is the complicated shape of the objects that makes it difficult to load the fixture automatically in a correct way. The operator can also check the weld quality directly and correct this if necessary. Some of the welds are covered in the next sequence of the assembly and are not possible to inspect afterwards on the completely finished arm.

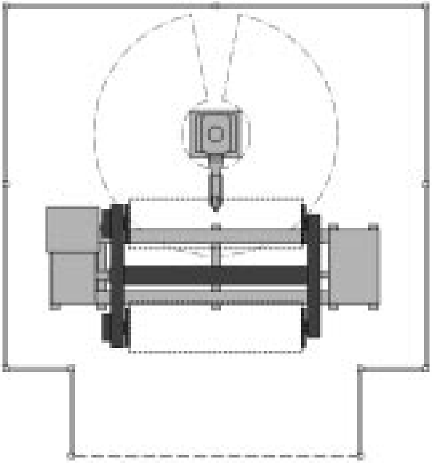
Depending on the number and complexity of the fixtures the availability of the robot line is lowered. The fixtures need regular adjustment.

17.2.2 Fixtures and robot movements

The fixing of the parts is done as follows. In the first station the fixture is stationary. The support arm is lifted from a conveyor band by the loading equipment and fixed in an optimum position. In order to optimise the welding time the longitudinal weld is divided into eight parts with different parameters and speeds. The robot changes the parameters without stopping. The welding speed differs between 25 mm/s down to as low as 10 mm/s depending on variations in gap width. The weld is welded in a flat position (PA). The weld around the tap is divided into three parts, two of which are welded partly vertically down (PG) and the end one in the overhead position (PE).

The second station has two identical fixtures mounted in a manipulator that rotates and makes it possible for the operator to safely load one fixture whilst another is welded (see Fig. 17.2).

The third station for completing the welding also has two identical fixtures in



17.2 The second station has two identical fixtures mounted in a manipulator that rotates.

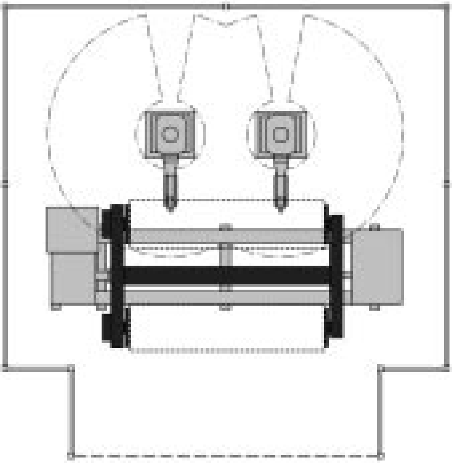
a two-station manipulator and two robots (see Fig. 17.3). These robots have the status of master and slave. Beside the six axes the master robot also controls the axes of the manipulator and is welding at the same time as the manipulator moves. Though it does not weld during station change. The slave robot can only weld when the manipulator is not moving. The manipulator in this station can move the fixtures between the robots and the operator but also rotate the fixture along the longitudinal axes of the support arm as well as tilt it sideways synchronically with the movements of the master robot. The reason for this is that the welding of the end piece should be in the best possible position. The weld between the end piece and the tube is very complicated because the joint geometry continuously changes around the obliquely cut tube.

In stations with two identical fixtures problems may appear in one of the fixtures leading to unacceptable quality of the part. In order to trace the reason an extra weld is performed on the part to mark which fixture has been used for the part concerned.

17.2.3 Preparation of the parts

The parts of the object must maintain very high requirements for dimensional tolerances since the tolerances of the final support arm are close. The tube is bent in two directions and very accurately cut obliquely. Small changes in strength of the material lead to a varying amount of springback. This must be allowed for, otherwise this leads to high wear of the tyres when driving the car.

Problems in the oblique cutting can give a varying gap between tube and end piece and risk weld defects and dimension variations.



17.3 The third station for completing the welding also has two identical fixtures in a two-station manipulator and two robots.

The arm with a butt joint is difficult to press because of the conical shape and the change from square edge to totally circular shape. For the forming of the arm 2.5 mm cut sheet metal is used. It is adjusted to get the right dimensions after pressing. The gap varies along the 860 mm long butt joint. This is solved in the welding by dividing the weld into eight parts each with individual welding parameters. It could have been easier to make the arm in two halves but that would mean two butt welds with a risk of deformation and dimensional problems.

The spring bracket is formed in a conventional press but the final cut that gives the right shape is made in a shuttle cut after the final forming. When a part is formed as much as this one, it is not possible to produce it from a tailor-made sheet billet.

17.2.4 Materials and welding

The car manufacturers try to minimise the weight of the cars. High-tensile steels are therefore preferred to reduce thickness and weight. Especially important for comfort is a low weight between spring and the road. If the support arm had been manufactured in high-strength steel it would have been lighter but because of the higher fatigue risks a normal strength steel is chosen. The sheet material is a low-alloyed steel with good formability and weldability. The end piece is made of press cast material.

The filler metal is a solid wire of quality EN 440 G 4 Si 1 diameter 1.0 mm. The somewhat higher alloyed solid wire compared to G 3 Si 1 compensates for the increased loss of alloying elements due to the higher oxidation by the shielding gas. A big packing with 250 kg of wire is used to avoid the changing of wire too often. The solid wire is checked regularly regarding the copper coating and cast and helix of the wire. The shielding gas used is an M23-shielding gas Ar/5CO_2/5O_2 for the butt weld in the arm, CO_2 for the other two stations. CO_2 as a shielding gas means more spatter and rougher surface. On the other hand wider penetration gives more safety against variations in the robot path and joint position. Due to limited space seam tracking is not possible. In the first station with a long butt weld low spatter, good surface appearance and high speed is preferred. In the other stations a wider penetration is first priority.

17.2.5 Programming

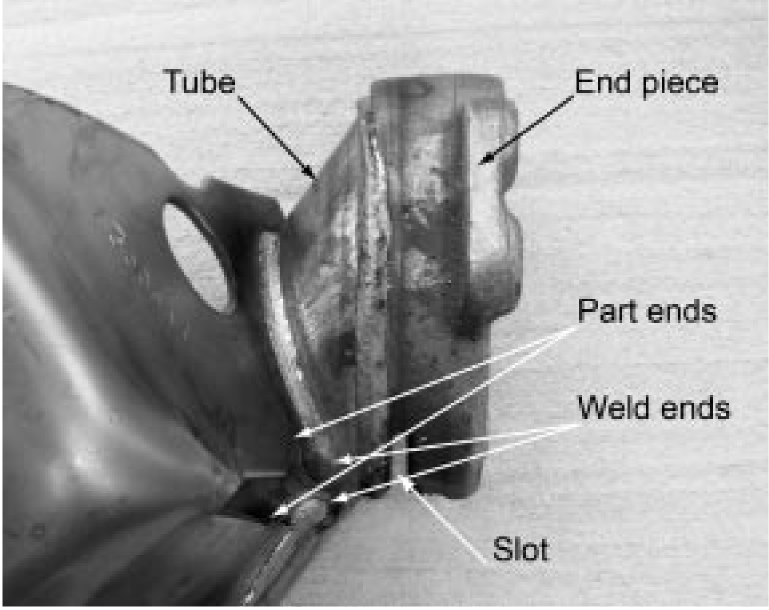
In order to optimise the cycle time the robots must weld as much as possible. Since the slave cannot weld when the fixture is moving it is very important that the programmer plans the fixture movements so that the waiting time for the slave robot is minimised.

The first programming of the final welding station was done by the robot supplier and led to a cycle time of almost four minutes. This programming was fairly well optimised but the robots waited for each other causing a fairly long cycle time. One of the company's own robot operators wrote a totally new program and the cycle time was reduced to less than two minutes. The reason mainly concerned minimising the time for robot movements and a program where the two robots are welding concurrently when the fixture does not move. The master/slave status was also changed. The quality was the same in both cases.

The support arm is heavily loaded in fatigue. By making the starts and stops of the welds on less loaded parts of the construction, geometrical defects were reduced and there was no fatigue cracking. Figure 17.4 shows the weld ends. An interesting solution was chosen when another model was welded. The wheelbase of this model was increased by 50 mm and the end piece thickness was changed from 11 to 36 mm. The only change was to put the fixture with the bracket for the end piece on a sleigh that could move 25 mm to and fro. The same assembly equipment could be used for both variants and it was simple and fast to change between them. The load on the weld increased because of the increased lever length between the fixing in the body and the wheel. The end piece became stiffer and fatigue cracks appeared between the tube and end piece. By milling a slot in the end piece to reduce the thickness against the most heavily loaded part of the tube from 36 mm to 8 mm, the risk of fatigue cracking disappeared. Note that the weld ends some millimetres out on the tube, which gives a better fatigue strength.

17.2.6 Transport to and from the robots

If manufacturing is to progress without disturbance the transport of details to and from the robot station and inside the robot station must be very reliable. One



17.4 Weld ends.

possibility might have been to have two or three manual trucks dedicated to this task with transport of a lot of details and objects. Another solution was chosen. An autocarrier system was built. The autocarrier takes the racks from storage and moves them to the robot station when requested by the operator. Empty racks are moved back to the storage. The racks are also used for transport between the different stations. The storage is both used as an intermediate storage and for finished products.

17.2.7 Quality control

All the welded support arms are primarily checked by the operator by visual inspection. One object per shift is submitted to destructive testing and the welds are inspected. The most critical welds are studied for each object, the less critical by a prearranged schedule. It is thus assured that no objects leave the factory without all welds being accepted.

17.2.8 General comments

In order to get a high reliability in production there must be a system of well-functioning preventive maintenance.

Total stops of the station are scheduled regularly for full maintenance. The operators change contact tubes twice a shift. A specially trained robot operator is available every shift and has the task of checking all the equipment. It is possible for the robot operator to notice problems before they influence the production. It has become evident that the role of this specialised operator is so important that he/she does not participate as an operator in the normal production. All the normal operators of the different robots and equipment must be well trained and certified for the job that they are doing.

17.3 Car body welding

The type of robot station presented in this application is totally different from the previous one. It is a part of a line for complete welding of car bodies and the details to be welded are already put in their right positions in the body before being fixed in the fixture for complete welding. In the main line there are included stations for floor, doors, bonnet, boot lid and many minor pieces. The application shown is the only MAG welding station in the line but there are also a number of resistance welding and laser welding stations in the main line.

17.3.1 Welding sequence

There are four robots in the station. Depending on the limited working space of the robots they cannot replace each other. The robots weld around the A- and D-pillar and the rear bumper on the right and left side (see Fig. 17.5). The station is fully automatic. The total cycle time is 65 seconds.

17.3.2 Materials and welding

The sheet steel thickness is between 0.8 and 1.2 mm and the steel is galvanised. The coating thickness is 10 μm. The rear bumper is made of a zinc-coated high-strength steel, 1.5 mm thick.

Some of the welds are visible on the finished car, which needs a good surface quality. A problem is that the body cannot be moved or tilted during welding. The best welding positions are not attainable and the welds must be completed in the actual positions. Some of the welds on the bumper must be made in the overhead (PE) position.

The filler material is a solid electrode with diameter 0.8 mm and quality EN 440 G 3 Si 1. Shielding gas is EN 439 – M 21 with 23% of CO_2. The filler metal is delivered in big packages. The gas is mixed in a gas mixer from argon and CO_2. The gas nozzle is regularly milled to remove debris from spatter and is then sprayed with an oil emulsion. The position of the welding gun is checked at the same time. Since the change between the stations takes 12 seconds there is enough time to make these checks without taking extra production time.

The weld shapes vary considerably and the space for the robot gun is very small. Therefore the use of seam tracking is not suitable. Instead the quality of

17.5 Robot station in the complete-body assembly line.

the parts and the check of the welding gun position assure the necessary quality.

17.3.3 Reliability and quality control

The quality of the welds is checked by visual inspection only. Therefore it is even more important to control all the parameters before welding.

The station has very limited buffers. There are four empty positions before and two after the station. A stop in the station of a few minutes will stop the whole main line. Preventive maintenance of the station, checks of the pieces on the body to minimize deviations in positions and gaps, control of filler material and shielding gas are the most important measures to get high reliability. This means that an availability of 99% has been reached during a couple of years.

The operators and the maintenance staff are a decisive factor in achieving this good result.

17.3.4 General comments

If a robotised line is to work continuously with an availability of 99% it is necessary that maintenance is very well planned and carried out. There must be easy access to the most frequently used spare parts. Before the introduction of robotic welding the welds were made manually and maintenance was not very critical. A power source that was not working could easily be replaced and another operator could also be found if there were problems.

After the introduction of robotic welding the maintenance became more critical. The robot could not be changed easily. The power source had to be calibrated for the robot before it could be used. The hose package and the welding gun can be changed but it takes time since it requires calibration in relation to the positions programmed for the robot. For example, it took four hours to solve a problem caused by a stop in the feeding of the solid wire in the wire-feed system. No new hose package was available and had to be delivered from the welding equipment supplier.

17.4 Acknowledgement

Thanks to Volvo Car Corporation in Göteborg and Olofstrom for permission to publish these two case studies.

17

Automotive applications of robotic MIG welding

R GUDMUNDSON, Air Liquide Gas AB, Sweden

17.1 Introduction

Robotic MIG welding is used extensively in automotive production for parts and for car bodies on the main production line. In both cases there is a high demand for quality and reliability as well as productivity. Two cases studies are presented below – welding of a rear support arm and welding car bodies on the main production line.

17.2 Rear support arm

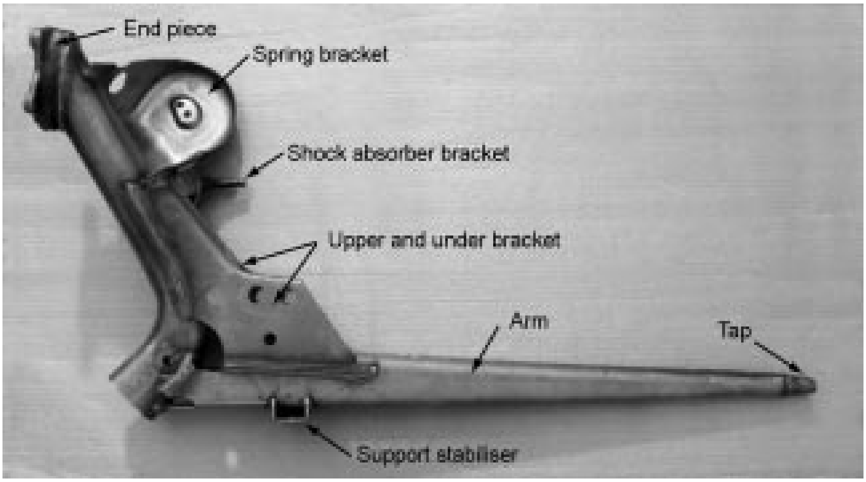
The rear support arm for a car is welded in a robot line. There is one robot line for the left and one for the right support arm. Figure 17.1 shows the left support arm. The rear wheels are screwed into the end piece with four bolts. The support arm acts together with a spring to transfer the weight of the car body to the wheels and the shock absorber, which prevents fast oscillations of the body when driving on roads of bad quality. The object is heavily loaded in fatigue.

The steel sheet has a thickness of 2.5 to 3 mm, but the end piece has a thickness of 11 mm in normal conditions but 36 mm in a model with 50 mm wider wheelbase. The total length of the welds is 3.0 m.

The series is 200,000 pieces per year with a maximum capacity in the robot line of 6000 support arms per week.

17.2.1 The welding sequence

The support arm is welded in three stations. In the first, the butt weld on the arm and overlap weld on the tap are welded by one robot. In the second, one robot welds part of the spring bracket and support stabiliser. In the third, with two robots the welding is finalised. The loading and unloading in the first station is fully automatic. The pieces are fed from a magazine and the welded parts are transferred to a rack that is automatically changed when filled. The second station is manually operated. Both loading and unloading of the fixture are done



17.1 Left support arm.

by one operator. The final complete welding station is also manually operated. The operator loads the support arm, the spring bracket, the upper and lower bracket and shock absorber bracket in the fixture. The reason for the manual operation of the two stations is the complicated shape of the objects that makes it difficult to load the fixture automatically in a correct way. The operator can also check the weld quality directly and correct this if necessary. Some of the welds are covered in the next sequence of the assembly and are not possible to inspect afterwards on the completely finished arm.

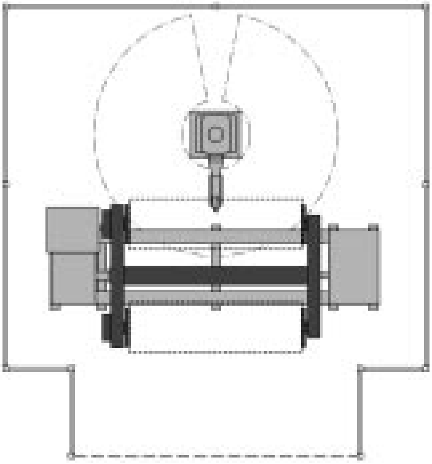
Depending on the number and complexity of the fixtures the availability of the robot line is lowered. The fixtures need regular adjustment.

17.2.2 Fixtures and robot movements

The fixing of the parts is done as follows. In the first station the fixture is stationary. The support arm is lifted from a conveyor band by the loading equipment and fixed in an optimum position. In order to optimise the welding time the longitudinal weld is divided into eight parts with different parameters and speeds. The robot changes the parameters without stopping. The welding speed differs between 25 mm/s down to as low as 10 mm/s depending on variations in gap width. The weld is welded in a flat position (PA). The weld around the tap is divided into three parts, two of which are welded partly vertically down (PG) and the end one in the overhead position (PE).

The second station has two identical fixtures mounted in a manipulator that rotates and makes it possible for the operator to safely load one fixture whilst another is welded (see Fig. 17.2).

The third station for completing the welding also has two identical fixtures in



17.2 The second station has two identical fixtures mounted in a manipulator that rotates.

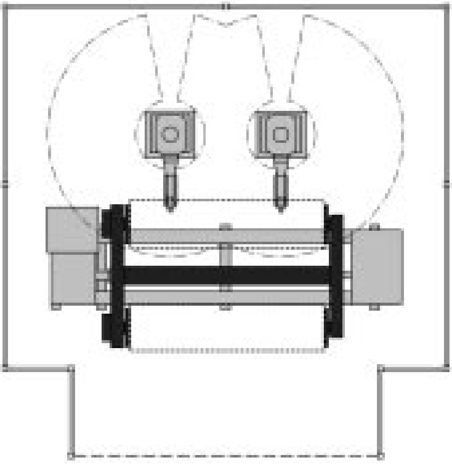
a two-station manipulator and two robots (see Fig. 17.3). These robots have the status of master and slave. Beside the six axes the master robot also controls the axes of the manipulator and is welding at the same time as the manipulator moves. Though it does not weld during station change. The slave robot can only weld when the manipulator is not moving. The manipulator in this station can move the fixtures between the robots and the operator but also rotate the fixture along the longitudinal axes of the support arm as well as tilt it sideways synchronically with the movements of the master robot. The reason for this is that the welding of the end piece should be in the best possible position. The weld between the end piece and the tube is very complicated because the joint geometry continuously changes around the obliquely cut tube.

In stations with two identical fixtures problems may appear in one of the fixtures leading to unacceptable quality of the part. In order to trace the reason an extra weld is performed on the part to mark which fixture has been used for the part concerned.

17.2.3 Preparation of the parts

The parts of the object must maintain very high requirements for dimensional tolerances since the tolerances of the final support arm are close. The tube is bent in two directions and very accurately cut obliquely. Small changes in strength of the material lead to a varying amount of springback. This must be allowed for, otherwise this leads to high wear of the tyres when driving the car.

Problems in the oblique cutting can give a varying gap between tube and end piece and risk weld defects and dimension variations.



17.3 The third station for completing the welding also has two identical fixtures in a two-station manipulator and two robots.

The arm with a butt joint is difficult to press because of the conical shape and the change from square edge to totally circular shape. For the forming of the arm 2.5 mm cut sheet metal is used. It is adjusted to get the right dimensions after pressing. The gap varies along the 860 mm long butt joint. This is solved in the welding by dividing the weld into eight parts each with individual welding parameters. It could have been easier to make the arm in two halves but that would mean two butt welds with a risk of deformation and dimensional problems.

The spring bracket is formed in a conventional press but the final cut that gives the right shape is made in a shuttle cut after the final forming. When a part is formed as much as this one, it is not possible to produce it from a tailor-made sheet billet.

17.2.4 Materials and welding

The car manufacturers try to minimise the weight of the cars. High-tensile steels are therefore preferred to reduce thickness and weight. Especially important for comfort is a low weight between spring and the road. If the support arm had been manufactured in high-strength steel it would have been lighter but because of the higher fatigue risks a normal strength steel is chosen. The sheet material is a low-alloyed steel with good formability and weldability. The end piece is made of press cast material.

The filler metal is a solid wire of quality EN 440 G 4 Si 1 diameter 1.0 mm. The somewhat higher alloyed solid wire compared to G 3 Si 1 compensates for the increased loss of alloying elements due to the higher oxidation by the shielding gas. A big packing with 250 kg of wire is used to avoid the changing of wire too often. The solid wire is checked regularly regarding the copper coating and cast and helix of the wire. The shielding gas used is an M23-shielding gas $Ar/5CO_2/5O_2$ for the butt weld in the arm, CO_2 for the other two stations. CO_2 as a shielding gas means more spatter and rougher surface. On the other hand wider penetration gives more safety against variations in the robot path and joint position. Due to limited space seam tracking is not possible. In the first station with a long butt weld low spatter, good surface appearance and high speed is preferred. In the other stations a wider penetration is first priority.

17.2.5 Programming

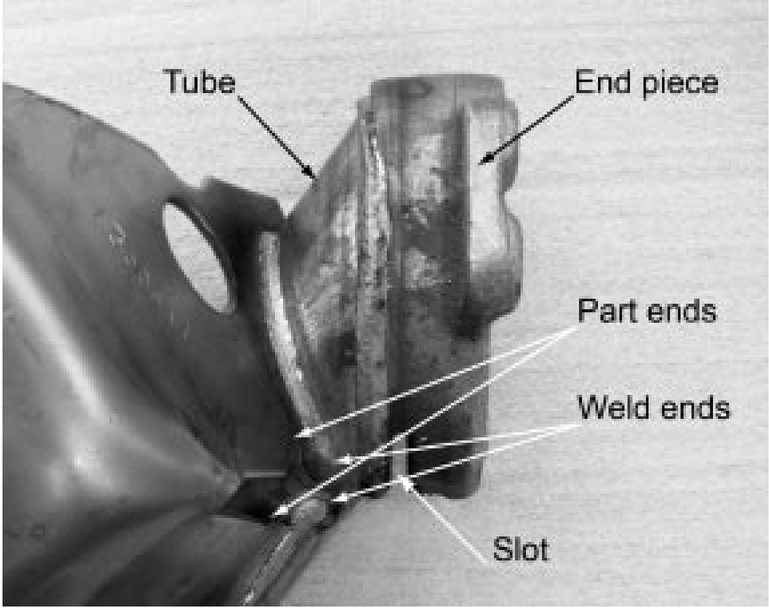
In order to optimise the cycle time the robots must weld as much as possible. Since the slave cannot weld when the fixture is moving it is very important that the programmer plans the fixture movements so that the waiting time for the slave robot is minimised.

The first programming of the final welding station was done by the robot supplier and led to a cycle time of almost four minutes. This programming was fairly well optimised but the robots waited for each other causing a fairly long cycle time. One of the company's own robot operators wrote a totally new program and the cycle time was reduced to less than two minutes. The reason mainly concerned minimising the time for robot movements and a program where the two robots are welding concurrently when the fixture does not move. The master/slave status was also changed. The quality was the same in both cases.

The support arm is heavily loaded in fatigue. By making the starts and stops of the welds on less loaded parts of the construction, geometrical defects were reduced and there was no fatigue cracking. Figure 17.4 shows the weld ends. An interesting solution was chosen when another model was welded. The wheelbase of this model was increased by 50 mm and the end piece thickness was changed from 11 to 36 mm. The only change was to put the fixture with the bracket for the end piece on a sleigh that could move 25 mm to and fro. The same assembly equipment could be used for both variants and it was simple and fast to change between them. The load on the weld increased because of the increased lever length between the fixing in the body and the wheel. The end piece became stiffer and fatigue cracks appeared between the tube and end piece. By milling a slot in the end piece to reduce the thickness against the most heavily loaded part of the tube from 36 mm to 8 mm, the risk of fatigue cracking disappeared. Note that the weld ends some millimetres out on the tube, which gives a better fatigue strength.

17.2.6 Transport to and from the robots

If manufacturing is to progress without disturbance the transport of details to and from the robot station and inside the robot station must be very reliable. One



17.4 Weld ends.

possibility might have been to have two or three manual trucks dedicated to this task with transport of a lot of details and objects. Another solution was chosen. An autocarrier system was built. The autocarrier takes the racks from storage and moves them to the robot station when requested by the operator. Empty racks are moved back to the storage. The racks are also used for transport between the different stations. The storage is both used as an intermediate storage and for finished products.

17.2.7 Quality control

All the welded support arms are primarily checked by the operator by visual inspection. One object per shift is submitted to destructive testing and the welds are inspected. The most critical welds are studied for each object, the less critical by a prearranged schedule. It is thus assured that no objects leave the factory without all welds being accepted.

17.2.8 General comments

In order to get a high reliability in production there must be a system of well-functioning preventive maintenance.

Total stops of the station are scheduled regularly for full maintenance. The operators change contact tubes twice a shift. A specially trained robot operator is available every shift and has the task of checking all the equipment. It is possible for the robot operator to notice problems before they influence the production. It has become evident that the role of this specialised operator is so important that he/she does not participate as an operator in the normal production. All the normal operators of the different robots and equipment must be well trained and certified for the job that they are doing.

17.3 Car body welding

The type of robot station presented in this application is totally different from the previous one. It is a part of a line for complete welding of car bodies and the details to be welded are already put in their right positions in the body before being fixed in the fixture for complete welding. In the main line there are included stations for floor, doors, bonnet, boot lid and many minor pieces. The application shown is the only MAG welding station in the line but there are also a number of resistance welding and laser welding stations in the main line.

17.3.1 Welding sequence

There are four robots in the station. Depending on the limited working space of the robots they cannot replace each other. The robots weld around the A- and D-pillar and the rear bumper on the right and left side (see Fig. 17.5). The station is fully automatic. The total cycle time is 65 seconds.

17.3.2 Materials and welding

The sheet steel thickness is between 0.8 and 1.2 mm and the steel is galvanised. The coating thickness is 10 μm. The rear bumper is made of a zinc-coated high-strength steel, 1.5 mm thick.

Some of the welds are visible on the finished car, which needs a good surface quality. A problem is that the body cannot be moved or tilted during welding. The best welding positions are not attainable and the welds must be completed in the actual positions. Some of the welds on the bumper must be made in the overhead (PE) position.

The filler material is a solid electrode with diameter 0.8 mm and quality EN 440 G 3 Si 1. Shielding gas is EN 439 – M 21 with 23% of CO_2. The filler metal is delivered in big packages. The gas is mixed in a gas mixer from argon and CO_2. The gas nozzle is regularly milled to remove debris from spatter and is then sprayed with an oil emulsion. The position of the welding gun is checked at the same time. Since the change between the stations takes 12 seconds there is enough time to make these checks without taking extra production time.

The weld shapes vary considerably and the space for the robot gun is very small. Therefore the use of seam tracking is not suitable. Instead the quality of

17.5 Robot station in the complete-body assembly line.

the parts and the check of the welding gun position assure the necessary quality.

17.3.3 Reliability and quality control

The quality of the welds is checked by visual inspection only. Therefore it is even more important to control all the parameters before welding.

The station has very limited buffers. There are four empty positions before and two after the station. A stop in the station of a few minutes will stop the whole main line. Preventive maintenance of the station, checks of the pieces on the body to minimize deviations in positions and gaps, control of filler material and shielding gas are the most important measures to get high reliability. This means that an availability of 99% has been reached during a couple of years.

The operators and the maintenance staff are a decisive factor in achieving this good result.

17.3.4 General comments

If a robotised line is to work continuously with an availability of 99% it is necessary that maintenance is very well planned and carried out. There must be easy access to the most frequently used spare parts. Before the introduction of robotic welding the welds were made manually and maintenance was not very critical. A power source that was not working could easily be replaced and another operator could also be found if there were problems.

After the introduction of robotic welding the maintenance became more critical. The robot could not be changed easily. The power source had to be calibrated for the robot before it could be used. The hose package and the welding gun can be changed but it takes time since it requires calibration in relation to the positions programmed for the robot. For example, it took four hours to solve a problem caused by a stop in the feeding of the solid wire in the wire-feed system. No new hose package was available and had to be delivered from the welding equipment supplier.

17.4 Acknowledgement

Thanks to Volvo Car Corporation in Göteborg and Olofstrom for permission to publish these two case studies.

18

Heavy vehicle applications of robotic MIG welding

H BROSTRÖM, Volvo Wheel Loaders AB, Sweden

18.1 Introduction

The development of robot technology has made it possible to use robotic welding of big, heavy objects with very long arc times for each object. It is possible to connect not only arc welding equipment but also other equipment to the robot station. Today it is common to see turntables, positioners, arc seam sensing and tracking, cameras, double-wire guns, etc. and twelve to fifteen axles that can work together in the robot cell with advanced control systems.

18.2 Welding of frames for heavy wheel loaders

18.2.1 The welding process

Heavy construction robot arc welding (HCRAW) uses MAG welding both with solid wire 1.2 mm and metal-cored wire 1.2–1.4 mm. The shielding gas is an argon–carbon dioxide mixture. The process development during the last five years has lead to the development of the twin-arc and tandem arc welding processes. The welding speed for single wire is on average 0.45 m/min and for double wire up to approximately 1.0 m/min. The use of two metal-cored wires in the tandem arc welding process gives a welding speed of 1.5 m/min when welding a throat thickness of 5 mm in the welding position PA (most favourable position).

Figure 18.1 shows a typical wheel loader.

18.2.2 Materials and preparation of the parts

The steel used is low-strength steel, thickness from 6 mm to 80 mm with an average thickness of 20–25 mm. The steel plates are shot blasted before the thermal cutting operation and the parts are straightened to within ±2 mm (see Fig. 18.2). The plasma cutting gives tolerances of ±1 mm. Some important location points, e.g. holes for location in tack-welding fixtures or in joints are machined with tolerances of ±0.2 mm. It is very important for the quality of the

18.1 Heavy wheel loader.

18.2 Straightening of steel plates.

welds and for achieving high welding speed that the tolerances of the parts are very tight.

One quality problem is the variations in thickness and hardness of the steel plates that give different spring-back in bending operations. The capability of the bending machine is therefore of great importance.

18.2.3 Fixtures and robot movements

The most complex fixtures are used in tack welding. After tack welding, the metal structures are fixed to the manipulators in the robot cell. Special adaptors are used in the manipulators. This gives the flexibility of welding different types and sizes of weld structure and also the possibility of welding in position PA.

Most heavy robot cells are of the gantry type that gives the optimum working range. The investment for such a heavy robot arc welding cell is from US$800,000 to US$1,000,000. In order to have an acceptable payback of this investment the robot cell must be used at least for two or perhaps three shifts.

18.2.4 Welding

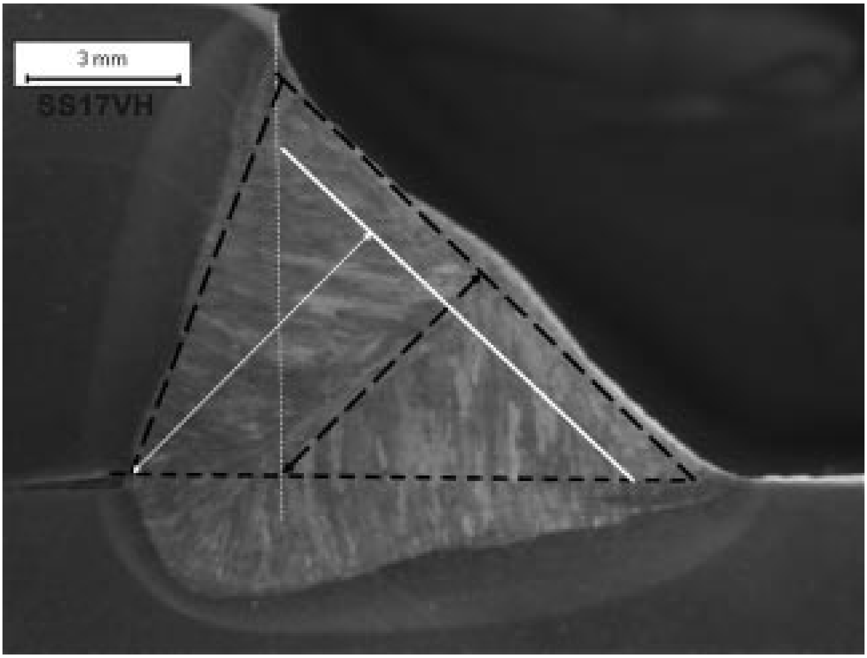
The deep penetration when welding with tandem arc welding and metal-cored wire will be 2–3 mm (see Fig. 18.3). This gives the possibility of reducing the visible throat thickness dramatically from, e.g. 8 mm to 6 mm and still have the same strength of welded joint. The shielding gas used in this process is Ar + 10% CO_2. (The gas is mixed in a mixer in the factory from argon and carbon dioxide.)

The requirements on the materials for this process are clean surfaces of the joint, no gaps and welding position PA. One big advantage with this method is that the welds get a concave shape, which gives higher fatigue strength. Some welds are also TIG dressed and the weld structures are shot-blasted (steel shots) afterwards which increases the fatigue strength even more.

18.2.5 Programming

It is possible to weld heavy structures in robots thanks to the gantry robot configuration (Fig. 18.4), and advanced robot programming. Robot programming was earlier a bottleneck since it was time-consuming and the robot had to be used during the programming. No production was possible for a long time. Today offline programming (OLP) is used. The utilisation of the robot is optimised and CADCAM technology makes it possible to transfer 3D-solid models from the design department to the manufacturing (see Fig. 18.5).

A successful design for robotic welding requires a long experience and close cooperation between the design department and the manufacturing department.



18.3 Fillet weld with good external shape and penetration, position PA. The weld is welded with tandem MIG welding and two metal-cored wires diameter 1.4 mm. Shielding gas was argon with 10% carbon dioxide, gas flow 25 l/min. Welding parameters 420 A and 32 V, stick-out 25 mm and welding speed 1.2 m/min. The theoretical throat thickness is 6 mm (black), the effective throat is 8 mm (white). It is possible to reduce the actual throat as is shown by the white line. The strength is at least the same as with the large throat (black dashed line). Also note the good connection between the weld metal and the base metal that favours a good fatigue performance.

18.2.6 Transport to and from the robots

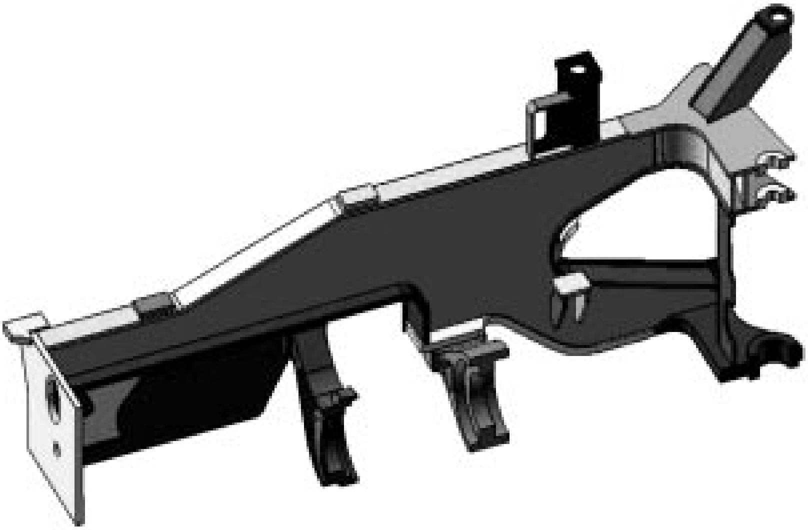
The frames are loaded with a crane onto the loading wagons, then the loading and unloading to and from the robot cell is done automatically.

18.2.7 Quality control

It is not possible to find defects inside the welds without using destructive testing. Such solutions are used for small objects where test samples are checked regularly. The control procedures of weld quality for heavy structures include a very strict control of the robot program, the welding parameters and the robot positioning during the welding. Welding inspection is done statistically by magnetic particle testing and ultrasonic testing.

The HCRAW process must be well adopted within the welding organisation.

18.4 Gantry robot with tandem arc welding equipment.



18.5 3D-CAD solid model of a side-section of a rear frame, which is also used in offline programming of the robot.

The cooperation between design and manufacturing, support from suppliers and the deep knowledge of the robot operator are all crucial elements for the success of the robot welding.

18.3 Future trends

Some trends in the future development of design and manufacturing of heavy earth-moving vehicles are:

- Increased use of high-strength steel:
  - Reduction of weight
  - More weight in the bucket
  - Less fuel consumption, less pollution, etc.
- Increase of the forces on the welds means that higher quality is required of the welds.
- Laser hybrid welding (laser–MIG welding):
  - Less residual stresses and less deformation
  - Higher welding speed
  - Deeper and better control of the penetration.
- Full automation of the whole robot welding line:
  - Lower operation time
  - Less manual handling.
- Integrated quality inspection system of the welds.

To reach these goals development is needed both in design and welding processes. A deeper understanding of the behaviour of the highly stressed welds under fatigue load is important and how to translate this into more precise calculation methods. With regard to processes, the laser hybrid welding is very interesting due to its high penetration.

Index