Steel Forgings:
Design, Production, Selection, Testing, and Application

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Foreword

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1

Introduction: Why Steel Forgings?

THE BEGINNINGS OF THE IRON AGE IN AUSTRIA about 3000 years ago mark the start of iron and steel forging, since at that time hot working by hammering was part of the process for producing wrought iron, and for making products in both wrought iron and steel. The crude smelting furnaces using high-grade iron ore, charcoal, and fluxes produced small quantities of iron that had to be forge welded together by hand to produce useful stock. Initially, this was the main purpose of forging. The hammers used were quite substantial, examples weighing about 80 lb (36 kg) having been found. Hand hammer working by smiths persisted as the main shaping procedure for iron and steel until the Middle Ages in Europe when lever operated Olivers were introduced. Several accounts of Olivers [1] have been traced to the north of England and one at Beaumarais Castle near Anglesey in North Wales in 1335. Their use continued into the eighteenth century. The Oliver consisted of a hammer attached to an axle by a long shaft that was tripped by a foot-operated treadle. A swing shaft then rotated the axle and raised the hammer for the next blow. A sketch (Fig. 1.1) from a book [2] published in 1770 gives some idea of the apparatus. As demand and the size of the iron blooms increased, the Olivers were superseded by water-powered tilt hammers. The melt and forge shops were generally close together since both operations went hand-in-glove; hence, the modern concept of an integrated melt and forge shop goes back a long way. An example of a water-powered tilt hammer at the Abbeydale Industrial Hamlet near Sheffield, England is shown in Fig. 1.2. Another tilt hammer design is shown in Fig. 1.3. This used the elastic energy from bending a wooden board to augment the gravity drop of the hammerhead.

It is generally acknowledged that the industrial revolution started in earnest with the commercial production in 1775 of James Watt's condensing steam engine. This facilitated the introduction of steam-powered mills that enabled wrought iron and later steel plates to be hot rolled.

The invention of the steam powered forging hammer, credited to James Nasmyth in 1839, met Isambard Kingdom Brunell's need for 30-in. (750-mm) diameter wrought iron propeller shaft forgings for the S.S. *Great Britain,* (Fig. 1.4), a bold stride forward in naval architecture. Nasmyth's painting of the forging operation for the shafting (Fig. 1.5) also illustrates the use of a porter bar by the forge crew to position the forging, a task that nowadays would be handled by a manipulator. A forging of this size was well beyond the capabilities of the water powered forging hammers available at that time. At over 60 ft (18 m) in length the propeller shaft (Fig. 1.6) is interesting because it was made by joining two 30-in. (750-mm) diameter wrought iron stub shafts (that ran in bearings) by a riveted iron cylinder. The wrought iron plates used for the cylinder were 6 ft by 2 ft and 1 in. thick (1800 × 600 × 25 mm). The four cylinder condensing steam engine developed 1600 horse power (1200 kW) from steam at 5 psi (35 kPa) raised from salt water. The ship was completed in Bristol in the South West of England in 1843 and made the first steam powered crossing of the Atlantic—unaided by sails—in 1845 at an average speed of 9.3 knots. Incidentally, this ship has been restored and now occupies the original dry dock in Bristol (Fig. 1.7) where she was built over 160 years ago.

Steel forgings, like hot rolled bar and plate, are the product of hot compressive plastic working used to consolidate and heal as-cast shrinkage voids and porosity, as well as break up the as-solidified structure of the product from the steel making furnaces. The availability of the steam hammer and the ability to work steel under it in different directions gave forgings the integrity that they are known for today. This improvement in material integrity and the ability to hot

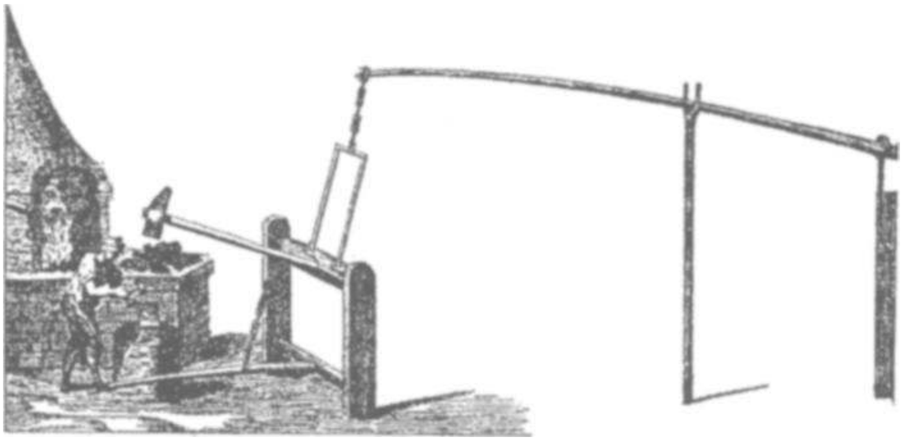


Fig. 1.1—The Oliver forging hammer.

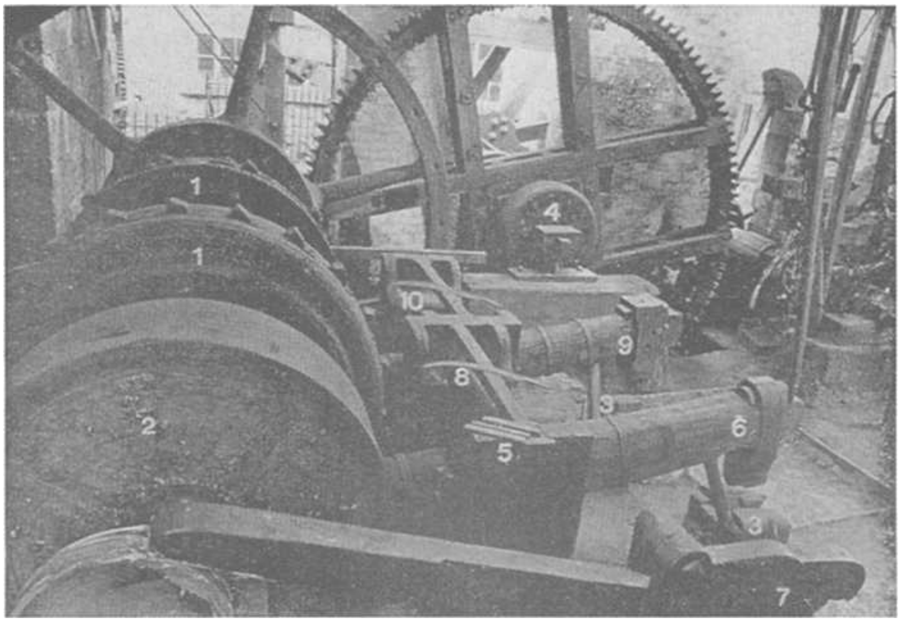


Fig. 1.2—Twin water powered tilt hammers at the Abbeydale Industrial Hamlet near Sheffield, England. This is a restored operating museum facility for demonstrating the art of scythe-making. The tilt hammers were lifted by a series of cogs set in iron collars (1) fitted on the drive shaft (2). As the shaft rotated the cogs lifted the hammers (6 and 9) and then fell under gravity on the anvils (3). The shaft was driven by the water wheel through an oak toothed spur wheel (4). The scythe starting stock (5) consisted of strips of steel that were heated in a coke or charcoal fired hearth and then forge welded together under the fast moving Steeling Hammer (6). This operated at 126 blows a minute when the main shaft rotated at 2 rpm. This forge welding operation produced a "Mood" that was then cut in half by the shears (7). After reheating the Mood halves were forged again under the Steeling Hammer to form "Strings" (8) that began to take the shape of a scythe blade. On further reheating the Strings were forged under the slower running Plating Hammer (9) at 66 blows/min to form the scythe blade, or "Skelp." (Courtesy Sheffield City Museums, Sheffield, UK)

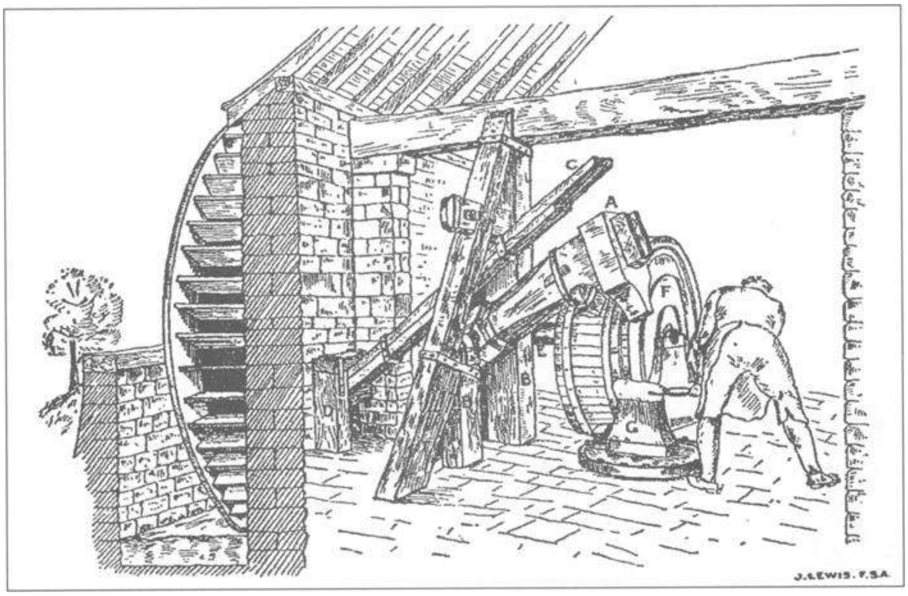


Fig. 1.3—Water powered forging hammer or Tilt Hammer. The cast iron hammer head "A" weighed about 500 lb (225 kg), and was attached to a wooden shaft about 9 ft (2.75 m) long. The opposite end of the shaft was fitted with a cast iron collar (b) that acted as a pivot. The water wheel drove a large wooden wheel called the "Arm-Case" (F) that was fitted with projecting iron tipped wooden blocks. As the arm-case rotated, the blocks engaged the hammer shaft and lifted it against a spring board (c) called a "Rabbet." After being lifted by the block, the hammer fell under gravity, assisted by the stored energy in the bent rabbet. The hammer averaged about 120 to 160 blows/min. (From D. Lardner: *Cabinet Cyclopaedia*, pp. 86–87, London 1831)

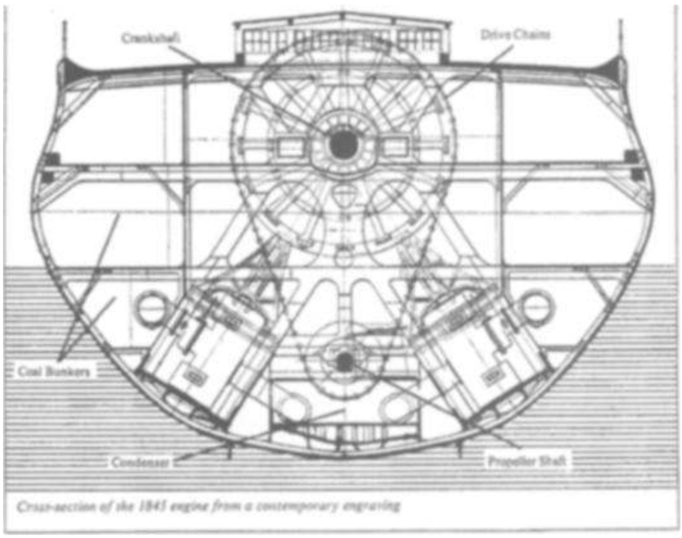


Fig. 1.4—A cross section through the hull of the S.S. *Great Britain* demonstrates the locations of the four cylinders of the Boulton Watt condensing steam engine, and the chain drive to the fabricated propeller shaft. To give an idea of scale, the beam of the vessel was 51 ft (15.5 m) and the chain drive wheel had a diameter of 18 ft (5.5 m) and a width of 38 in. (950 mm). The four cylinder steam engine had 88 in. (2200 mm) pistons. (Courtesy of The Great Britain Project, Bristol, UK)

work the wrought iron or steel close to the required contour became the attributes associated with forging today.

At this point it should be noted that cold forging used to shape relatively small parts uses hot worked starting stock.

It is not proposed to discuss the various steel making processes in any great detail here, but it should be noted that these do have an effect on the properties of the hot worked material made from them, and influence some differences between forgings and hot rolled plate. An excellent overview of steel making and processing is included in a book entitled *The Making, Shaping and Treating of Steel* [3].

A definition of a forging was written by ASTM Committee A01 on Steel, Stainless Steel, and Related Alloys and was published about 40 years ago as ASTM A 509, Standard Definition of a Steel Forging. This was discontinued in 1985 when it was incorporated into ASTM Specification A 788, Steel Forgings, General Requirements. The current text is short and is worth repeating here:

> Steel Forging—The product of a substantially compressive plastic working operation that consolidates the material and produces the desired shape. The plastic working may be performed by a hammer, press, forging machine, or ring rolling machine and must deform the material to produce an essentially wrought structure. Hot rolling operations may be used to produce blooms or billets for reforging. Forgings may be subdivided into the following three classes on the basis of their forging temperatures.
>
> 1. Hot-worked forgings—forgings produced by working at temperatures above the recrystallization temperature for the material.
> 2. Hot-cold-worked forgings—forgings worked at elevated temperatures slightly below the recrystallization temperature to increase mechanical strength. Hot-cold worked forgings may be made

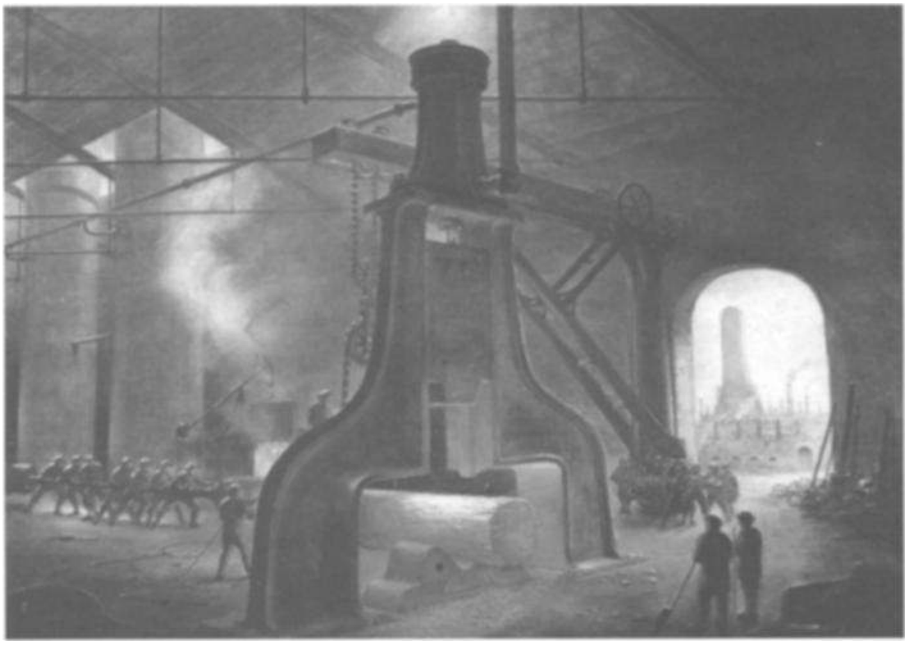
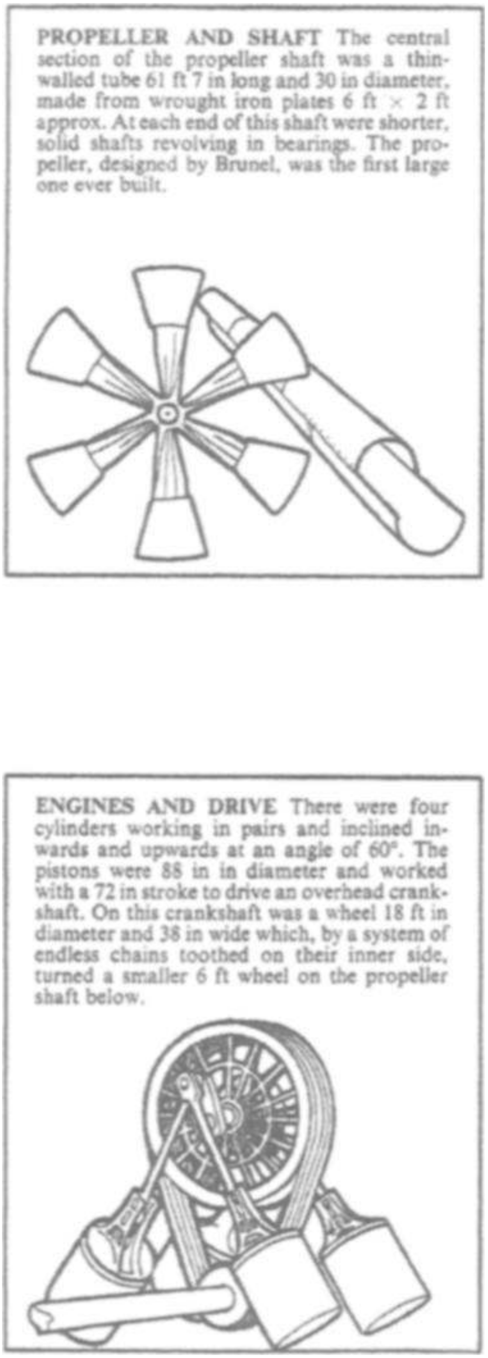


Fig. 1.5—James Nasmyth's painting of his patented steam hammer forging the propeller shaft stubs for Isambard Kingdom Brunel's S.S. *Great Britain*. These were the largest wrought iron forgings of the day. Notice the manually operated crane, and the porter bar crew rotating the forging and passing it between the dies. (Courtesy of The British Museum Science Collection)



PROPELLER AND SHAFT The central section of the propeller shaft was a thin-walled tube 61 ft 7 in long and 30 in diameter, made from wrought iron plates 6 ft × 2 ft approx. At each end of this shaft were shorter, solid shafts revolving in bearings. The propeller, designed by Brunel, was the first large one ever built.

ENGINES AND DRIVE There were four cylinders working in pairs and inclined inwards and upwards at an angle of 60°. The pistons were 88 in in diameter and worked with a 72 in stroke to drive an overhead crankshaft. On this crankshaft was a wheel 18 ft in diameter and 38 in wide which, by a system of endless chains toothed on their inner side, turned a smaller 6 ft wheel on the propeller shaft below.

Fig. 1.6—Sketches of the *Great Britain* propeller shaft fabricated from riveted wrought iron plates and forged wrought iron bearing stubs. The relationship of the four-cylinder steam engine and the chain drive to the propeller shaft is shown also. (Courtesy of The Great Britain Project, Bristol, UK)

from material previously hot worked by forging or rolling. A hot-cold-worked forging may be made in one continuous operation wherein the material is first hot worked and then cold worked by control of the finishing temperature. Because of differences in manufacture hot-rolled, or hot and cold finished bars (semi-finished or finished), billets or blooms are not considered to be forgings.

Fig. 1.7—The S.S. *Great Britain* under restoration in the Great Western dry dock in Bristol, UK where the keel was laid in 1839. (Courtesy of The Great Britain Project, Bristol, UK)

3. Cold-worked forgings—forgings produced by plastic working well below the temperature range at which recrystallization of the material occurs. Cold-worked forgings must be made from material previously hot worked by forging or rolling.

The wrought product forms for steel include plate, shapes, bar, sheet, strip, tubes, pipes, extrusions, and forgings. Generally, extrusions are included with forgings, but the definition of a forging excludes rolled plate and bars. This is because forgings, besides conforming approximately to the finished shape of the required component, are not expected to exhibit the traits of laminar inclusions through thickness weakness sometimes associated with hot rolled plate, or the central unsoundness sometimes associated with hot rolled bar. These points will be discussed in more detail later.

References

[1] Schubert, H. R., *History of the British Iron and Steel Industry from 450 BC to AD 1775*, Routledge and Kegan Paul, London, 1957.

[2] Young, A., *A Six Month Tour Through the North of England*, Vol. 2, 1770, p. 256.

[3] *The Making, Shaping and Treating of Steel*, United States Steel Corporation.

2

Why Use Forgings?

FORGING, AS A METAL WORKING PROCESS, HAS the ability to form the material to the desired component shape, while refining the cast structure of the ingot material, healing shrinkage voids, and improving the mechanical properties of the material. The amount of subsequent machining should also be reduced, although this depends on the geometry of the finished part and the forging processes used.

Cast ingots were the traditional starting point for forgings, either forging directly from the ingot, or from a bloom or billet that had been hot worked from an ingot. With the wide use of strand (continuously) cast steel, this source is now commonly used as the initial stock and, since the cast shape can closely resemble that of the wrought bloom or billet, lengths of this material are frequently referred to as billets or blooms. To avoid confusion, Specification A 788 requires continuously cast material that has not received hot working, to be supplied and identified as cast billets or cast blooms.

The choice of manufacturing route may be dictated by the required properties in the part, integrity criteria, or simply economics. Frequently all of these apply.

Steel Plate

Hot rolled plate material is ideally suited to flat shapes, as for example in parts of a ship's hull, and can be formed readily into curved or cylindrical shapes. Directional properties in plate tend to vary between the longitudinal and transverse directions depending on the relative amounts of rolling work in each direction. Some control of this is exercised in the ASTM steel plate specifications in that the required tension tests are taken from transverse test specimens that are oriented at right angles to the direction of major rolling work. During fabrication or in some service applications where rolled plate can be stressed in the through thickness or short transverse direction, serious problems have arisen due to a marked reduction in tensile ductility in this orientation, sometimes referred to as the short transverse direction. Although this problem can be overcome at some cost, the use of a forging could be considered.

Hot Rolled Bar

Rolled bar, by virtue of the manufacturing process, tends to have markedly different properties in the direction of rolling (longitudinal) as compared to the transverse direction, and this should be taken into account when specifying it. The effects of hot work applied during rolling tend to be more pronounced on the outer fibers of the starting stock as compared to the central area, and this effect becomes more pronounced as the bar diameter or cross section increases. This problem limits the size of hot rolled bar, depending on the mill capacity to a maximum of about 14 in. (350 mm). Rolled bar is frequently used as starting stock for forgings.

Steel Castings

Steel castings offer another method of producing shapes, particularly if there are contained bores or chambers, such as is the case for valve bodies or complex items like turbine steam chests. While castings have an advantage in that the mechanical properties tend to be isotropic, particularly if solidification has been controlled to avoid coarse columnar grains, the mechanical properties tend to be lower than those of an equivalent wrought product. Additionally, it is common for the mechanical test specimens to be taken from separately cast keel bars from the same heat. These may represent material capability rather than the actual properties of the casting itself.

The prospect of shrinkage cavities in castings is always present, together with the risk of defects associated with gat-

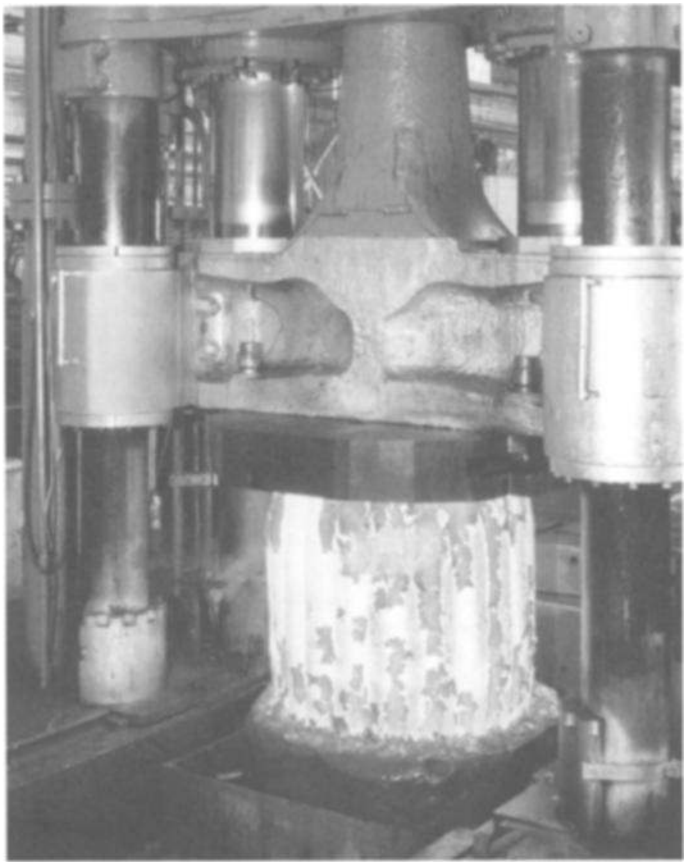


Fig. 2.1—Upset forging, compressing the ingot to reduce the axial length and increase the diameter. The length after upsetting is typically half of the initial length. (Courtesy A. Finkl and Sons Company)

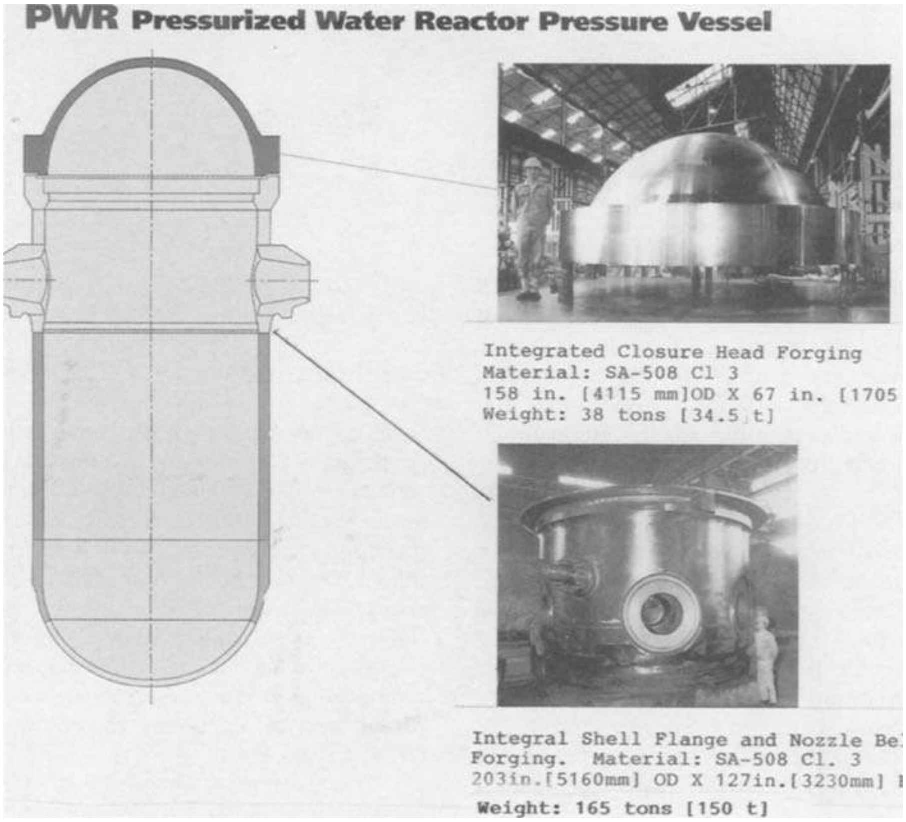


Fig. 2.2—Integrally forged shell flange and nozzle belt and integral flange and closure head forging for a PWR vessel. Forgings to SA-508/SA-508M Class 3 are preferred for these nuclear reactor vessel components. (Courtesy of the Japan Steel Works Ltd.)

ing, runners, and feeder heads. This means that extensive nondestructive examination and weld repair have to be allowed for especially in critical products. By the nature of the casting process reoxidation of the steel during casting and hydrogen pick up are ever present risks.

Steel Forgings

Because of the functions that they are intended to fill, forging designs frequently include large heat-treated section sizes, and may be of irregular shape, so that significant stresses may be applied in service in all three principal axes, i.e., longitudinal, transverse, and short transverse. By careful selection of the starting ingot size and forging steps it is possible for a forging to exhibit favorable properties in all three directions. In other instances, for example, in an upset disk forging (Fig. 2.1), favorable mechanical properties can be obtained in a radial direction around the full circumference, something that would not be possible in a disk that was simply cut from a rolled plate.

Fabrication by welding from plate, bar, and tube can and has supplanted forgings in some applications. For example, in the days of riveted construction, the development of hollow forged monoblock steam drum forgings for water tube boilers enabled thicker drum walls to be made than was practical for riveted seams. This enabled steam pressures to be increased with consequent improvement in efficiency. Improvements in welding processes and procedures enabled

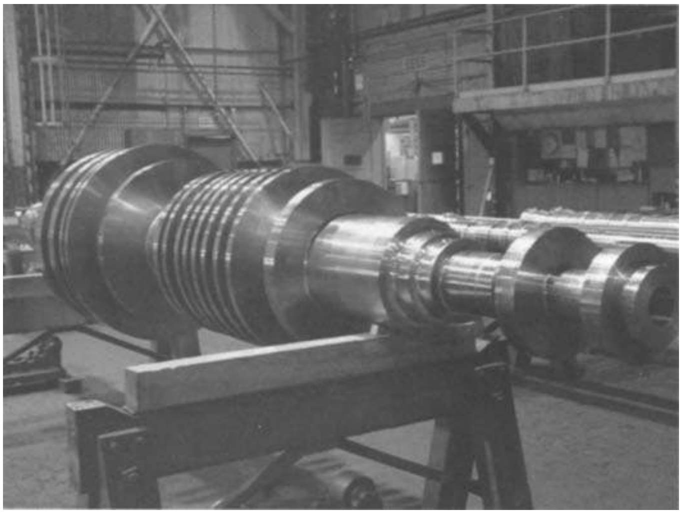


Fig. 2.3—Rough machined steam turbine rotor ready for final machining and installation of the turbine blades. Mechanical test specimens have been taken from the bore shown on the right. Ultrasonic examination to ASTM Specification A 904 could be applied to a bore of this size. (Courtesy Ellwood National Forge Company)

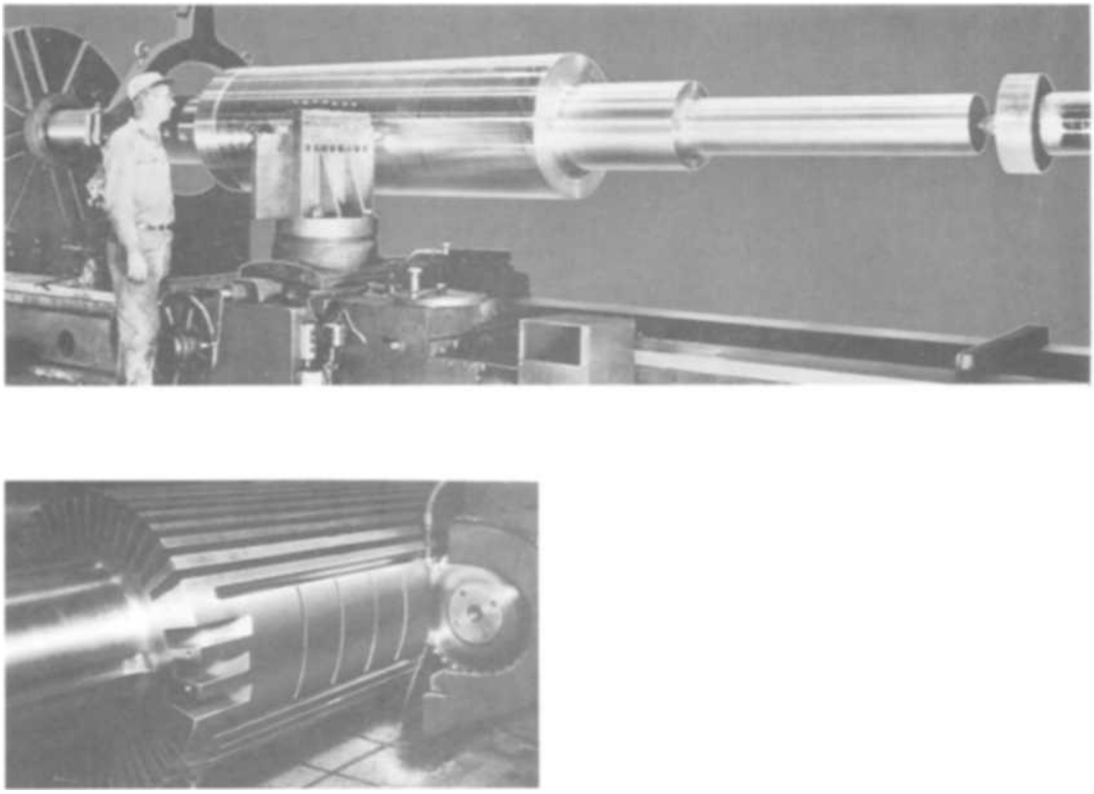


Fig. 2.4—Rough machined generator rotor forging, and typical slotting operation for the generator windings. (Courtesy Westinghouse Corporation)

Fig. 2.5—Continuous grain flow, closed die forged diesel electric locomotive crankshafts. The counterweights were welded to the webs before heat treatment. (Courtesy Ellwood National Crankshaft Company)

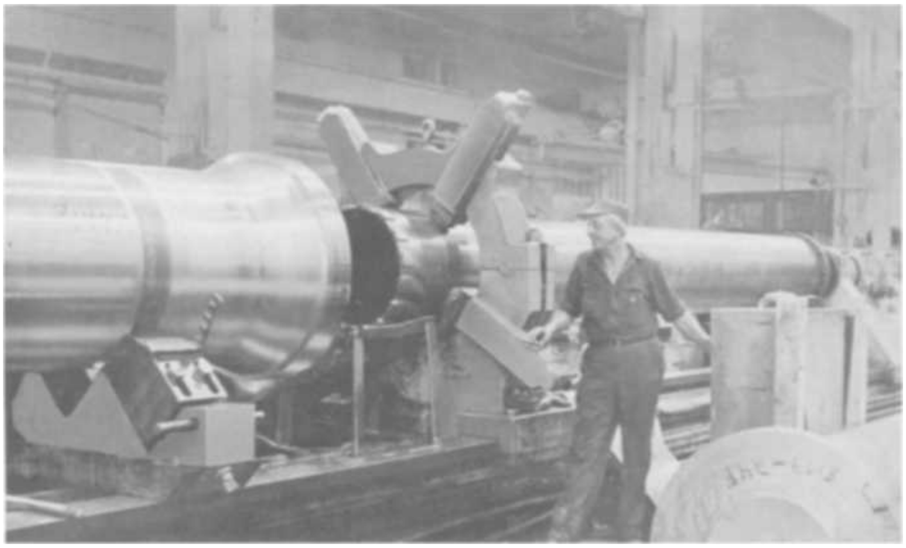


Fig. 2.6—Trepanning the bore of a large forged steel centrifugal casting mold. The core bar is typically used as starting stock for other applications.

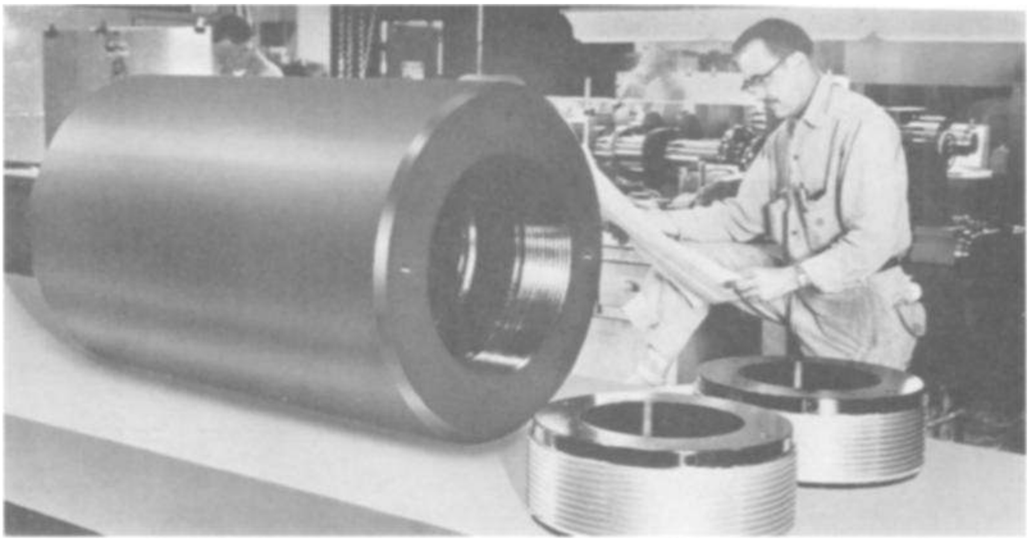


Fig. 2.7—Forged high strength alloy steel pressure vessel with threaded closures. Interrupted breach threading for rapid closing and opening is often used in this type of pressure vessel. Wall thicknesses up to about 14 in. (350 mm) have been used for such vessels.

high-pressure boiler drums to be made from rolled and welded plate. These drums could be made larger in terms of both diameter and length by this procedure. Although one-piece forgings fell out of favor for this application, the use of specially forged components such as nozzles that were welded into the drums became more common, adding enhanced integrity to the assembly. While this combination of forged components and rolled plate has become a standard practice for major components such as boiler drums, the use of forged rings joined by circumferential welds has become popular for large vessels such as catalytic crackers in oil refineries, and for the nozzle belt (Fig. 2.2) in some nuclear reactors.

Forgings then are the manufacturing method of choice for critically loaded items, such as turbine and generator rotors (Figs. 2.3 and 2.4), crankshafts (Fig. 2.5), centrifugal casting molds (Fig. 2.6), high strength pressure vessels (Fig. 2.7), marine propeller shafts (Fig. 2.8), ordnance components (Fig. 2.9) and pressure containing parts such as nozzles (Fig. 2.10), extrusion containers (Fig. 2.11), pump housings (Fig. 2.12) and piping fittings (Fig. 2.13).

Within the specification and application of steel forgings, certain manufacturing methods lend themselves to quantity production and product quality. Structural grain flow in a forging is a sought after quality in terms of application reliability and performance, particularly when fatigue

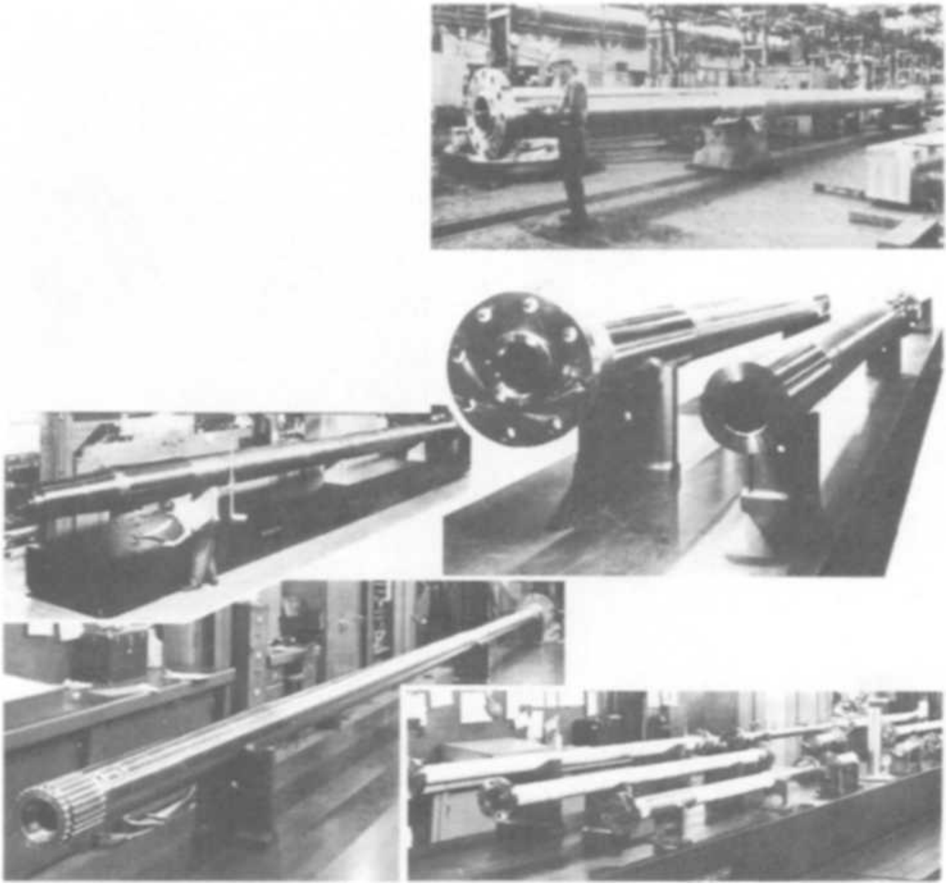


Fig. 2.8—Examples of forged shipshafts with integral flanges in carbon and alloy steels. The propeller shaft shown at the bottom left side was made from Monel for a nonmagnetic minesweeper application. Shaft sections up to about 40 ft (12 m) in length can be produced depending upon the application; however, individual section length is often dictated by factors such as accessibility in the ship so that multiple flanged joints are required.

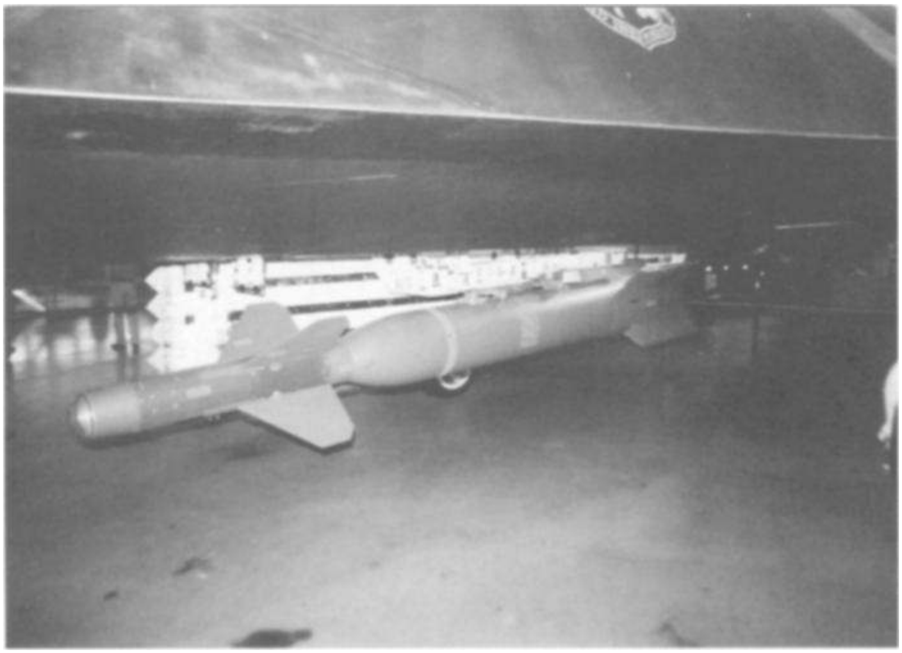


Fig. 2.9—Guided 2000 lb (905 kg) penetrator warhead in an aircraft bomb bay. The warhead, shown here between the nose guidance kit and the aft fins, was made from a high strength quenched and tempered Ni-Cr-Mo-V alloy steel forging.

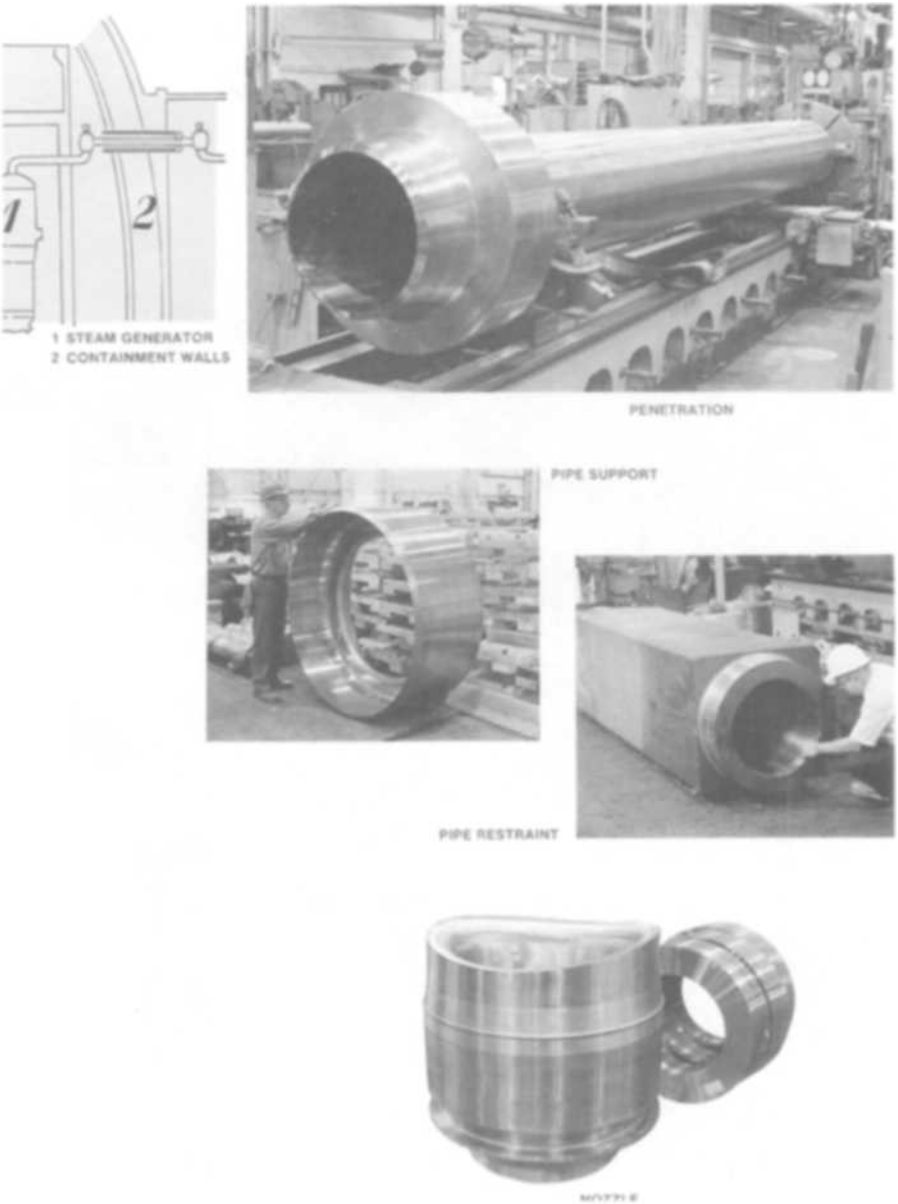


Fig. 2.10—Nuclear reactor vessel nozzle alloy steel forging to SA-508, Class 3, main steam pipe penetration carbon steel forging to SA-266, Grade 2, and main steam pipe support and restraint, both forged to SA-266, Class 2.

strength is of importance. In part, at least, this is because nonmetallic inclusions are aligned with the direction of working and are least troublesome when this alignment is maintained in the finished part, hence the desirability of contour forging.

Closed die forging often achieves this goal, but carries the burden of die costs and necessary volume of production, as well as equipment power and availability. The slab (solid) forged crankshaft and the continuous grain flow crankshaft are good examples of forging production methods developed to meet specific market and application needs.

Slab forged crankshafts are so called because the forged blank is typically made from a big end up forging ingot (Fig. 2.14) that is forged into a long rectangular slab (Fig. 2.15), thick enough to machine the bearing and crankpin journal diameters, and with offset stub shafts at each end, with perhaps a coupling flange. Bear in mind that the major segregation in the ingot lies along the central axis, so that this now runs along the centerline of the slab section, and has been diverted to run through the centerline of the offset arms. The slab must now be laid out to mark the positions of the main bearings and crankpin journals, and after rough milling and turning, is shown ready for twisting (Fig. 2.16). The twisting operation sets each crankpin section in its required angular orientation, and is done by locally heating the adjacent main bearing sections to about 1900°F (1040°C). After twisting (Fig. 2.17) the excess material in the crankpin block is removed. Drilling, sawing, and flame cutting are frequently used at this stage to prepare for turning the crankpins (Fig. 2.18).

The finished marine diesel engine crankshaft (Fig. 2.19) in this case includes an integral compressor crankshaft, an

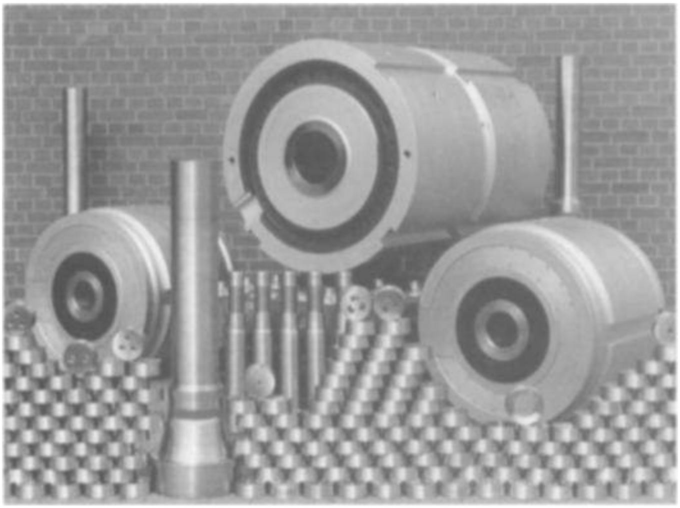


Fig. 2.11—Forged multi-walled containers used in the extrusion of ferrous and nonferrous materials. Containers are usually made from two or more concentric cylinders assembled by shrink fitting. The largest container in this example had an OD of 48 in. (1200 mm) and an ID of 12 in. (300 mm) and an overall length of 50 in. (1250 mm). The three part assembly of mantle or outer jacket, liner holder, and liner weighed about 22 000 lb (10 t). Associated stems and dies are also shown. Another reported example [1] for a 14 350-ton (1300 t) extrusion press had a container OD of 88 in. (2200 mm) and an ID of 18 in. (450 mm) and a length of 126 in. (3150 mm). (Courtesy of Schmidt + Clemens + Co., Lindlar Germany)

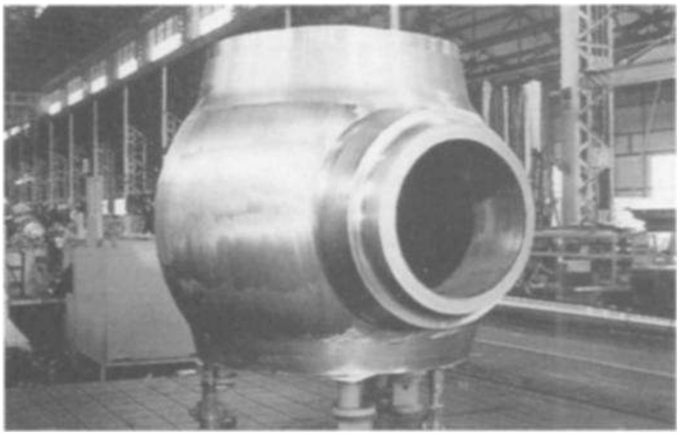


Fig. 2.12—Forged Boiling Water Reactor (BWR) circulating pump housing to SA-508 Class 3. Outside diameter 96 in. (2400 mm) and 77 in. (1930 mm) high. Weight 16 tons (14.5 t). (Courtesy of The Japan Steel Works, Ltd.)

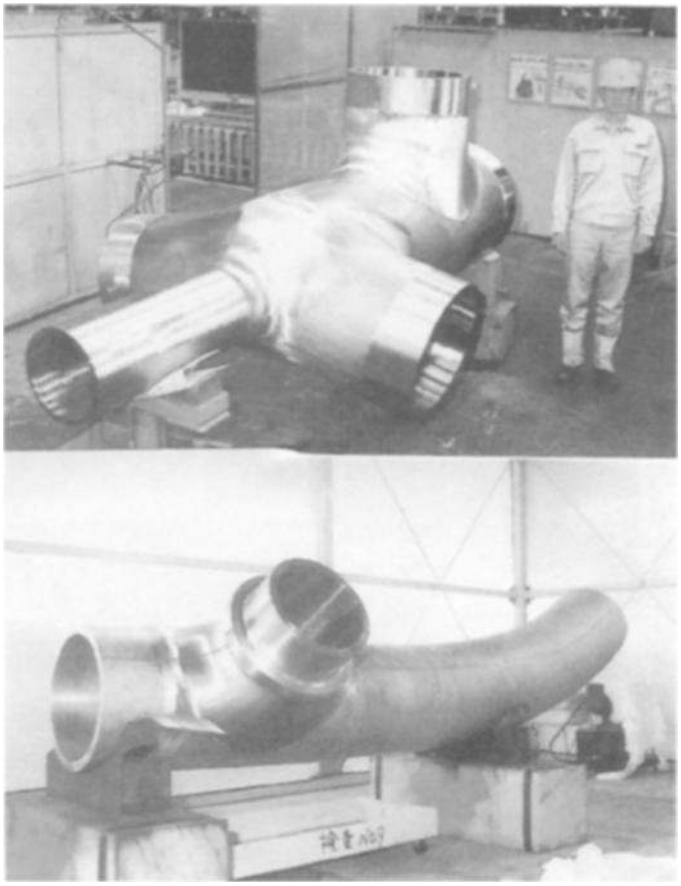


Fig. 2.13—Large austenitic stainless steel forged piping fittings in Grade F316LN for a Pressurized Water Reactor (PWR) piping system. The fitting in the upper picture weighed 2 tons (1.8 t) and in the lower picture 1 ton (0.9 t). (Courtesy of The Japan Steel Works, Ltd.)

important item for a submarine. It is seen that the central axis of the original ingot now runs close to the critically loaded areas of the crankpins and the main bearings. This location brings potential problems for material quality that can show up in both ultrasonic and magnetic particle examinations. These will be discussed during reviews of the product specifications; they reflect the need to carry out preliminary ultrasonic examinations at stages much before the minimum requirements of test methods and practices such as ASTM A 388/A 388M, Ultrasonic Examination of Heavy Steel Forgings.

References

[1] Wagner, H., Schonfeld, K. H., Meilgen, R., and Dincher, T., "Outfitting a 13000 Tonne Extrusion Press with Two Four Part Containers," *14th International Forgemasters Meeting*, Wiesbaden, Germany, September 2000, pp. 356–361.

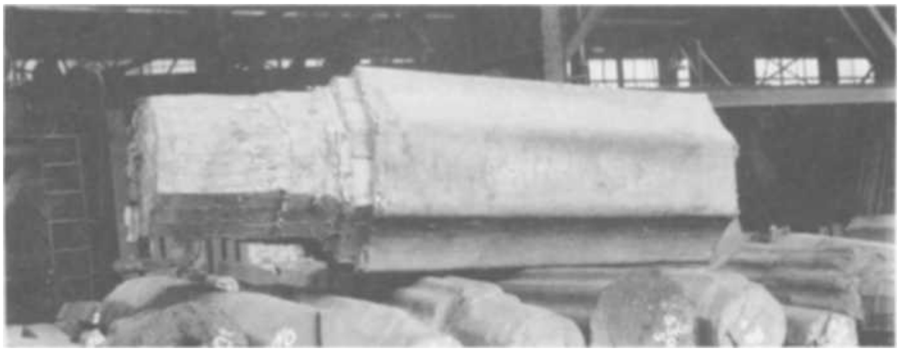


Fig. 2.14—Alloy steel big end up, octagonal fluted forging ingot with hot top or feeder head. Ingot diameter 42 in. (1050 mm), and weight 44 000 lb (1993 kg). Used to forge one of three sections for the slab forged crankshaft shown in Fig. 2.19.

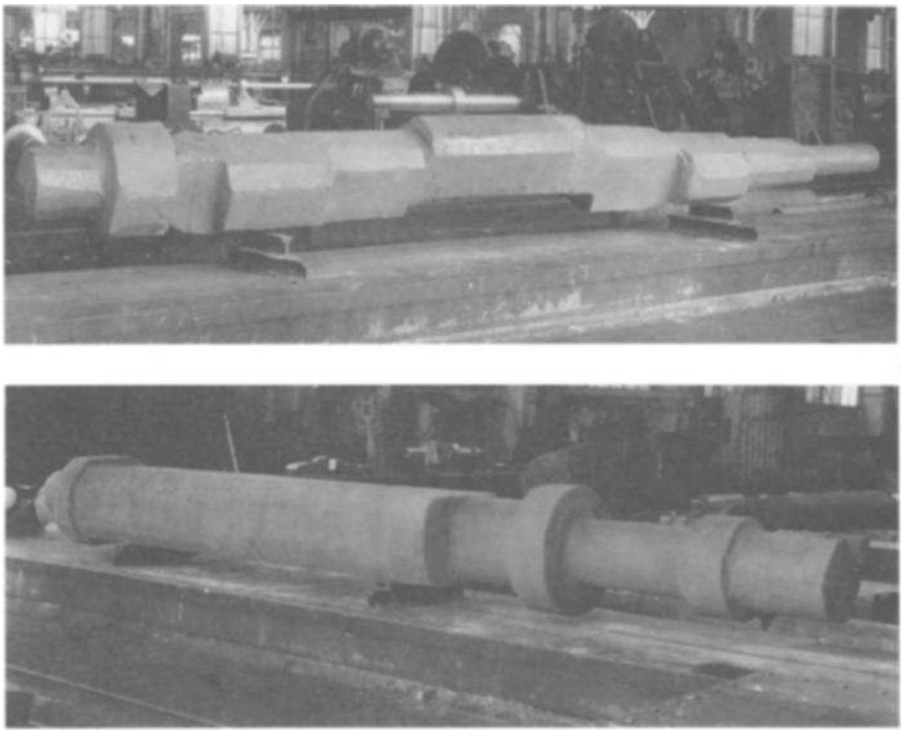


Fig. 2.15—Slab forgings for two of the three sections of the crankshaft. In the case of the first section that includes the integral compressor crankshaft, the slab section was forged to minimize the amount of twisting for the crankpin throws.

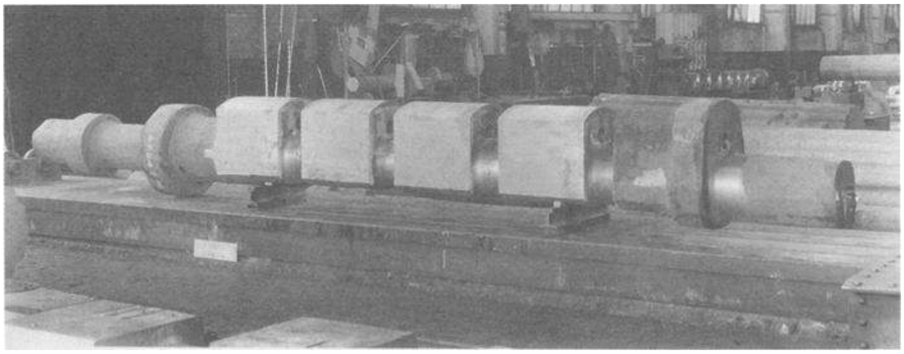


Fig. 2.16—Slab notched and bored prior to twisting the crankpins into their correct orientations. The main bearings are shown rough machined.

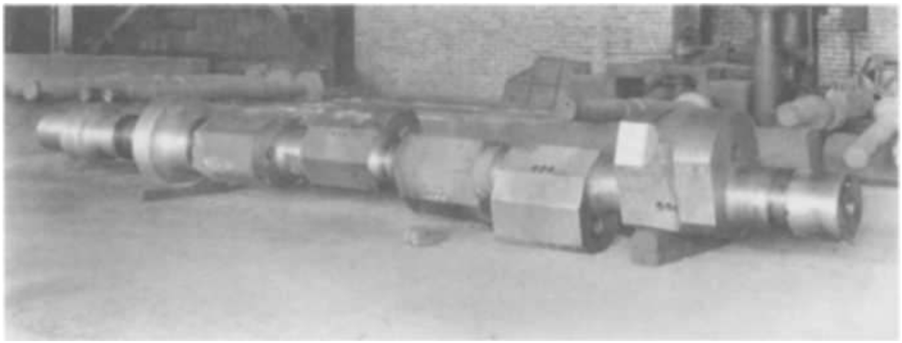


Fig. 2.17—Crankpins after hot twisting, and drilled prior to sawing excess material from the crankpin locations.

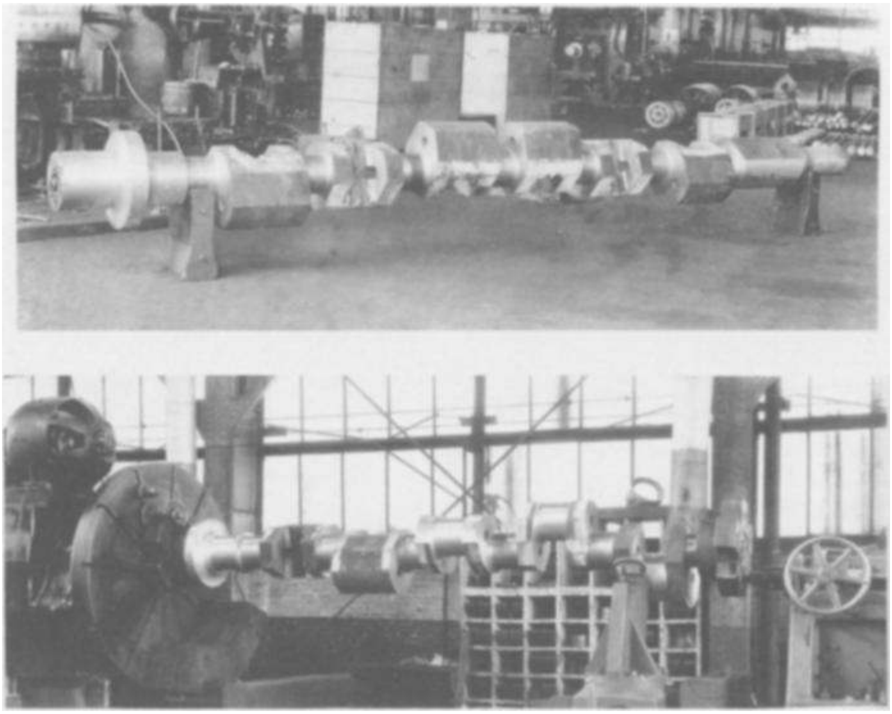


Fig. 2.18—Crankshaft after notching the crankpins and during rough machining. The main and crankpin bearing journals were 9.5 in. (238 mm) in diameter.

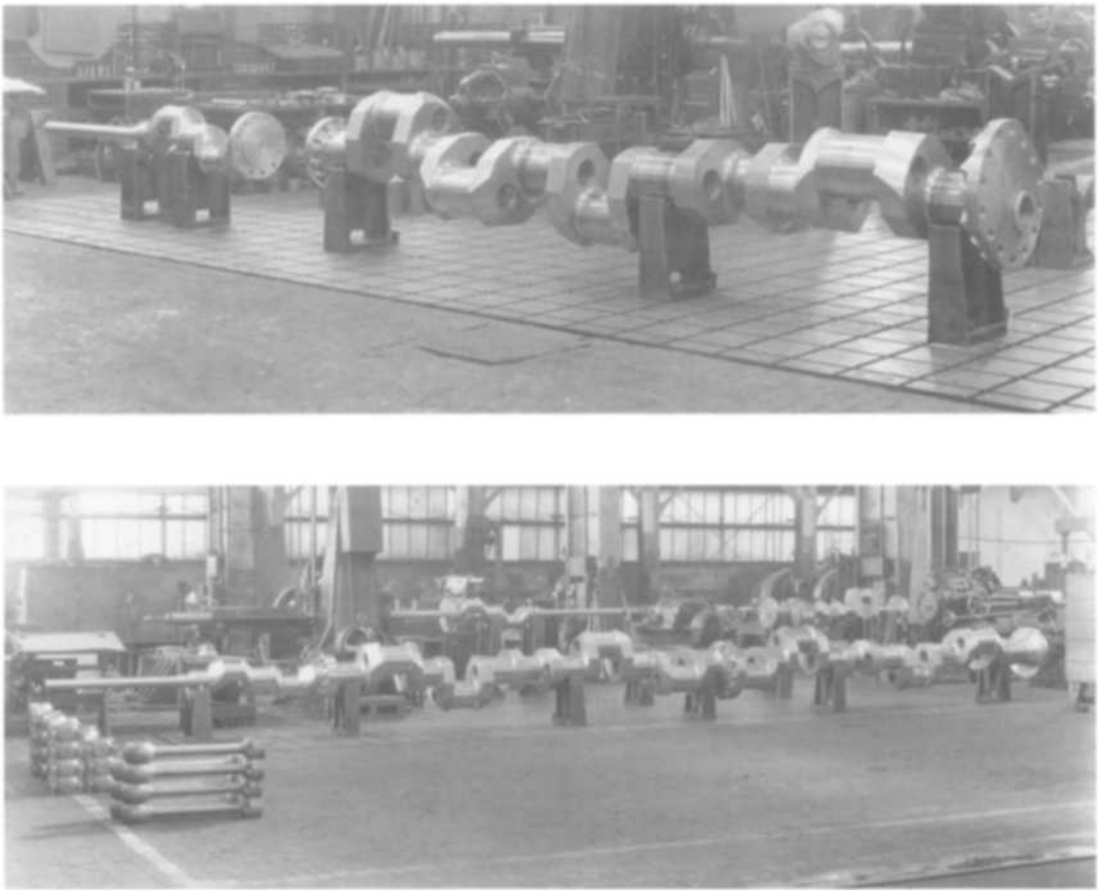


Fig. 2.19—Finished crankshaft with attached compressor shaft for a submarine diesel engine. The assembly had a length of 40.75 ft (12.4 m). Two were purchased for submarines V-5 and V-6 for the U.S. Navy in 1927. This method of manufacture continues today for small quantity production. Notice the forged connecting rods in the foreground.

3

Effect of Steel Making

THE NEED FOR IMPROVED MECHANICAL PROPerties and soundness in forgings has been a driving force in both steel making and ingot development, and it is perhaps significant that at one time many steel forging companies operated integrated facilities starting at the melt shop, and besides the forge, including heat treatment equipment, machine shops, and extensive mechanical testing and nondestructive examination facilities. This trend has changed with the increased complexity of steel melting practices and the growth of steel melting shops that provide stock for forging houses, either in the form of ingots or shapes from continuous casters.

In the early part of the last century, steel was produced largely in the acid and basic open-hearth furnaces and by pneumatic processes such as Bessemer and Thomas converters, with the electric furnace making its first appearance before becoming the steel making method of choice.

It is of interest to note that when a forging heat is required to be especially low in residual alloying elements, such as chromium, nickel, and molybdenum, the furnace charge relies heavily on steel plate scrap originally made from blast furnace pig iron.

Steel making processes are generally described according to the type of refractory lining used in the steel making furnace, and are classified as being either acid or basic [1]. In the acid process the linings are of the siliceous type. This type of refractory precludes the use of the lime-based slags (because these would attack the acid refractories) that are necessary for removal of phosphorous and sulfur from the steel. The acid processes, therefore, are restricted to the use of low sulfur and phosphorous charges, and frequently use a single slag. The basic processes use furnace refractories, such as magnesite and dolomite, suited for the use of the basic steel making slags that facilitate the removal of phosphorous and sulfur from the steel. A double slag process is most often used for these steels.

The old pneumatic hot metal processes, such as the Bessemer (acid) and Thomas (basic) converters that were blown with air, gave way to the acid and basic Open Hearth (OH) furnaces that could also use molten pig iron. In some instances steel from an air blown converter was combined with open hearth refining in what were called duplex and even triplex processes.

Later developments from about 1952, using converter vessels blown with oxygen gave rise to a series of basic oxygen steel making processes. Examples are the Linz-Donawitz or LD process, the Kaldo, and Q-BOP processes. These are top blown using an oxygen lance, as opposed to the bottom air blown Bessemer and Thomas converters. A full description of these processes is included in a major publication, *The Making, Shaping and Treating of Steel* [1].

For steel forging production the primary steel source is the electric furnace, particularly using a double slag process and preferably coupled with vacuum degassing and secondary refining.

In terms of bulk steel making today, continuous or strand casting is the most widely used method of providing the steel product, and in consequence, this process is frequently used in the production of forgings. The solidification characteristics of cast steel can produce central looseness or shrinkage, and a significant central segregation zone, and much development has gone into mitigating these effects in continuous casting. The question of the minimum required hot working reduction for this material, however, has been a source of disagreement over the years. In ASTM Specification A 20/A 20M, General Requirements for Steel Plates for Pressure Vessels, a minimum reduction ratio of 3:1 is required for continuously cast plate blooms, but this ratio can be reduced to 2:1 for plate 3 in. (75 mm) and greater in thickness, provided that tightened quality assurance items are followed including 0.004 % maximum sulfur, vacuum degassing and through thickness tension testing. This points to the importance of close control of the steel making process. As in conventional ingot practice, the risk of quality problems tends to increase with increasing ingot or cast bloom size.

Steel Refining

The advent of secondary ladle refining, whereby steel is melted and the phosphorous content reduced in the electric furnace, followed by refining in a ladle furnace, has enabled the production of steel with a quality rivaling that of the Vacuum Arc Remelting (VAR) and Electro Slag Remelting (ESR) processes. This in no small measure can be attributed to the close temperature control and the ability to vacuum degas that the equipment permits. The success of this type of equipment is reflected in the publication of a third steel cleanliness rating specification by the Society of Automotive Engineers [2]. Specifications AMS 2300, Steel Cleanliness, Premium Quality, and AMS 2301, Steel Cleanliness, Aircraft Quality, long represented electric furnace steel product (AMS 2301) and remelted steel produced by the Vacuum Arc Remelting (VAR) or Electroslag Remelting (ESR) procedures (AMS 2300). A third standard, AMS 2304, Steel Cleanliness, Special Aircraft Quality, now represents ladle refined steels.

As mentioned earlier, in basic electric furnace steel making, the usual practice for forging applications is to use the double slag procedure. The scrap charge is melted under an oxidizing basic slag, and the initial or melt-in carbon content is intended to be about 0.25 % higher than the final aim. Oxygen is blown into the heat to assist in oxidizing the carbon, silicon, manganese, and notably phosphorous in the steel. At the end of the oxidizing period, the slag is removed, and with it a significant amount of phosphorous, and the reducing slag is prepared. The reducing slag consists of burnt lime, fluorspar, and silica with coke added to form calcium carbide. The object here is to take sulfur into the slag and to alloy the heat as required before tapping into the ladle. Grain refining additions are usually made just before tapping, or during vacuum degassing. From there the steel can be teemed into ingot molds, or delivered to the tundishes of a continuous caster. Vacuum degassing and inclusion shape control can be done in the ladle prior to teeming, or the steel can be vacuum stream degassed during teeming.

Ladle Refining Furnace (LRF)

A ladle refining system that was developed by Union Carbide for the manufacture of stainless steels is known as Argon Oxygen Decarburization (AOD). In this the steel, first melted in the electric arc furnace, is tapped into the AOD converter. Argon is bubbled through the heat in the vessel through tuyeres in the bottom, and oxygen is blown in from the top by means of a lance. Carbon dioxide and monoxide formed by reaction with the carbon in the heat are swept away with the argon so that equilibrium is not established. This system enables the low carbon austenitic stainless steel grades to be made economically, without severe chromium loss, such that the higher carbon stainless steel grades are now made by the same process and recarburized to bring them into range. The method when applied to low alloy steels is very effective in reducing the sulfur content while lowering hydrogen in the bath to about 2 ppm as well. Temperature in the converter is maintained by the oxidation of elements such as silicon.

Perhaps inspired by the success of the AOD process, attention was turned to the development of separate Ladle Refining Furnaces (LRF). In this steel making procedure, the electric furnace is used to melt down the charge under an oxidizing basic slag for phosphorous removal, after which the heat is transferred to a ladle unit for the refining stage. Here temperature can be controlled by an electric arc, as in the electric furnace, and sulfur can be removed to extremely low levels, less than 0.001 % if necessary. Alloying additions and vacuum degassing round out the process before tapping, and at all times temperature can be finely controlled. The economics of the process permit utilization of the electric furnace, during off peak power demand periods, to melt steel while the ladle furnace, because of its lower power consumption, can be used during higher demand times to finish the heats. Several ladle refining systems have evolved, some of which utilize separate stations where the ladle is sequentially loaded for heat refining or degassing, while others use the ladle itself as part of a processing station. Argon flushing is used to assist in degassing and stirring, and induction stirring is also employed in such installations. Ladle refining is now an essential part of a modern steel plant, but regardless of the equipment available, how it is used determines the steel quality. A schematic description of a typical process is shown (Fig. 3.1).

Ladle additions after degassing can be used for deoxidation and to trim the steel composition, although there is the ever present risk of hydrogen pick up. The extent of these ladle additions is significantly limited by steel temperature considerations because steel quality is highly dependent on the ingot teeming temperature.

Vacuum Degassing

The presence of hydrogen in steel forgings has long been recognized as a serious problem because of reduced tensile ductility and the risk of internal ruptures known as *Flake or Flaking*. This defect manifests itself, after an incubation period, as randomly oriented fissures that are often located in a ring about midradius to one third of the diameter from the surface. The fissures are typically intergranular and if broken open generally exhibit a light colored flat appearance. Hydrogen has some solubility in liquid steel—about 12 ppm can be expected—and is present during all steel making operations, except those done under vacuum. While some hydrogen is lost on solidification, a significant amount, probably of the order of 3–4 ppm, is retained in the austenitic phase. The solubility of hydrogen in austenite decreases markedly on the transformation to ferrite and pearlite or other transformation products. The diffusion of nascent hydrogen in the steel after transformation to sites such as nonmetallic inclusions leads to pressure build-ups that cause local rupturing, thus forming the fissures. If flake is identified at an intermediate stage in forging, often the material can be reforged to heal the fissures enabling a flake prevention cycle to be applied as part of the post forge heat treatment cycle. Flake is highly detrimental to forging integrity, and can readily act as an origin site for a fatigue failure or brittle fracture.

As Robert Curran explained in his keynote address to the Committee A01 Steel Forging Symposium [3] in 1984, the vacuum degassing of forging steels was hastened by the incidence of hydrogen related problems facing the producers of rotor forgings in the late 1950s. The use of acid open hearth steels gave relief from hydrogen problems at the expense of steel cleanliness, but the basic open hearth steel, though cleaner, had higher hydrogen contents and the basic electric furnace steels, though cleaner than either of the open hearth processes, were the most hydrogen prone of the three. The use of higher steam pressures and temperatures in the generating plant increased operating efficiency, but imposed higher stresses both on the turbine and generator rotors, and several costly failures occurred in this period. In addition, the ability to conduct volumetric examinations in large steel sections by ultrasonic methods was being developed and this enabled deep-seated defects, such as flake, in rotor forgings to be detected. Although not all of the failures were attributed to the presence of flake, the situation was critical enough for rapid installation of vacuum degassing equipment to process steel for forging ingots.

Vacuum degassing of molten steel first appeared commercially in Europe during the early 1950s using vacuum mechanical pumps; however, it became more of a reality with the introduction of multiple stage steam ejectors and evolved into two main systems. These were Vacuum Stream Degassing (Fig. 3.1) and Vacuum Lift (Figs. 3.2, 3.3) processes.

In the vacuum stream degassing system, a large bell-shaped vessel fitted with a refractory lined tundish is placed over the ingot mold or a second ladle. The vessel is evacuated to a low pressure, less than 1000 μm, typically about 400 μm. A ladle stopper rod in the tundish, or pony ladle as it is sometimes called, enables the vessel to be evacuated. The furnace ladle is brought into position over the tundish and tapped and then the tundish is opened to allow the steel to

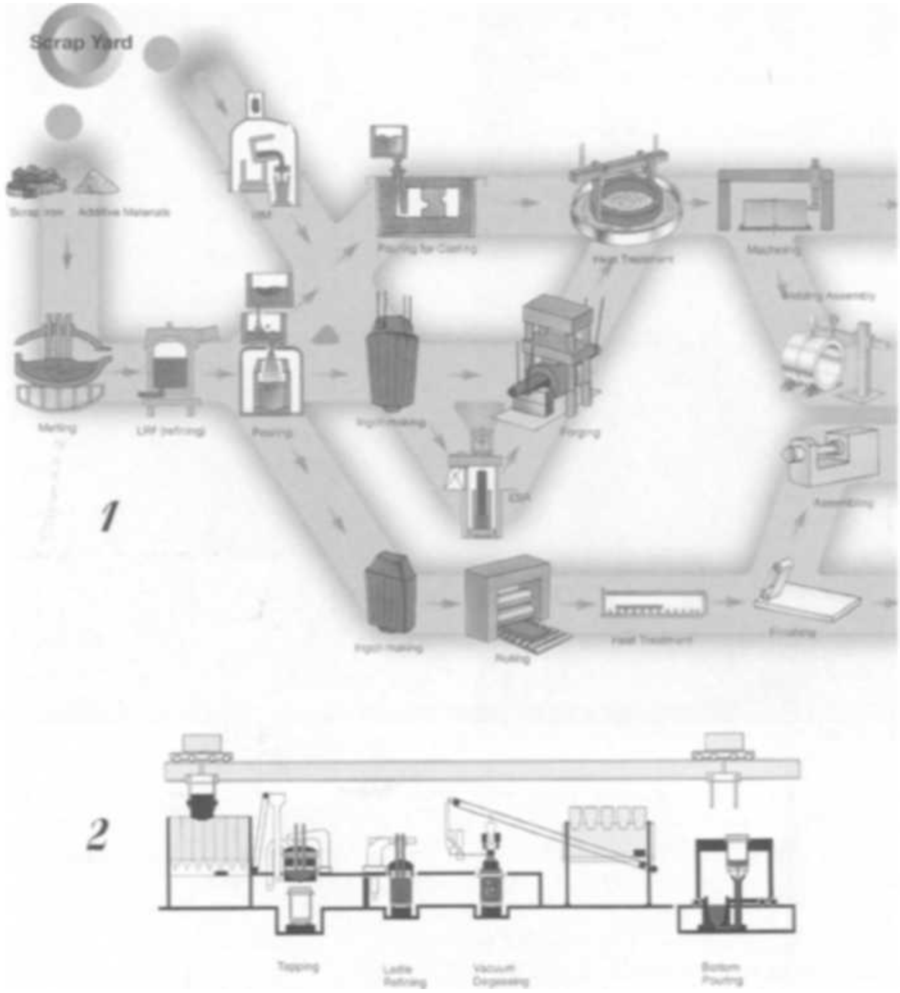


Fig. **3.1**—Schematic diagrams of typical current steel production stages for forgings. In Diagram 1, for a large integrated forging operation, molten steel from several electric arc furnaces is refined in ladle refining furnaces (LRF) before being combined during vacuum stream degassing into an ingot mold. Large ingots up to 600 tons (544 t) can be made in this way. In Diagram 2 smaller electric furnaces supply molten steel to the LRF to be followed by vacuum degassing and ingot production by bottom pouring under argon shrouding. (1. Courtesy of the Japan Steel Works, Ltd. 2. Courtesy Ellwood National Forge Company)

flow into the vacuum chamber. Under the vacuum conditions in the bell the steel stream breaks up into droplets, exposing large surface areas to the vacuum, permitting efficient degassing. The ingot is allowed to solidify in the bell before being removed for stripping, or the degassed steel in the receiving ladle is transferred to a pit for conventional ingot teeming in air. An important metallurgical benefit from this procedure was recognized over 40 years ago at Erie Forge and Steel in Erie, Pennsylvania [4], so that vacuum stream degassing into the mold became de rigueur in the manufacture of generator and steam turbine rotor forgings, pressure vessels, and ordnance components. This benefit was that while under vacuum, carbon in the steel droplets reacted with oxygen in the steel to form carbon monoxide gas that was swept away together with the hydrogen, thus deoxidizing the steel without solid oxides of silicon or aluminum being left behind. To enable this clean steel practice to work, the silicon had to be kept to a maximum of 0.10 %, and a special provision for this was included in the rotor specifications. It is now increasingly common for fully killed forging steels to have a maximum silicon content rather than a range so that the clean steel benefits obtained by vacuum stream degassing can be enjoyed also in steels made by the vacuum ladle refining processes.

Vacuum stream degassing is the preferred route for making very large forging ingots involving multiple heats. Such ingots are used for large rotor forgings and combined nuclear reactor components [5].

For the vacuum lift procedures a smaller vacuum vessel is used, and the steel is degassed in a series of cycles where only part of the heat is exposed to the vacuum at a time. One such method, the Dortmund-Hörder or DH system uses a refractory lined and heated cylindrical vacuum vessel, and a provision to add trim alloys and deoxidizers under vacuum,

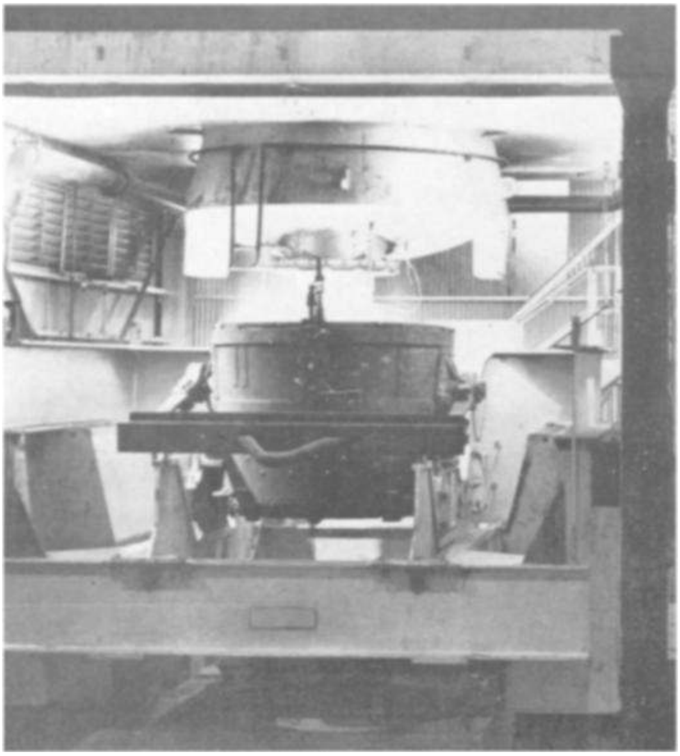
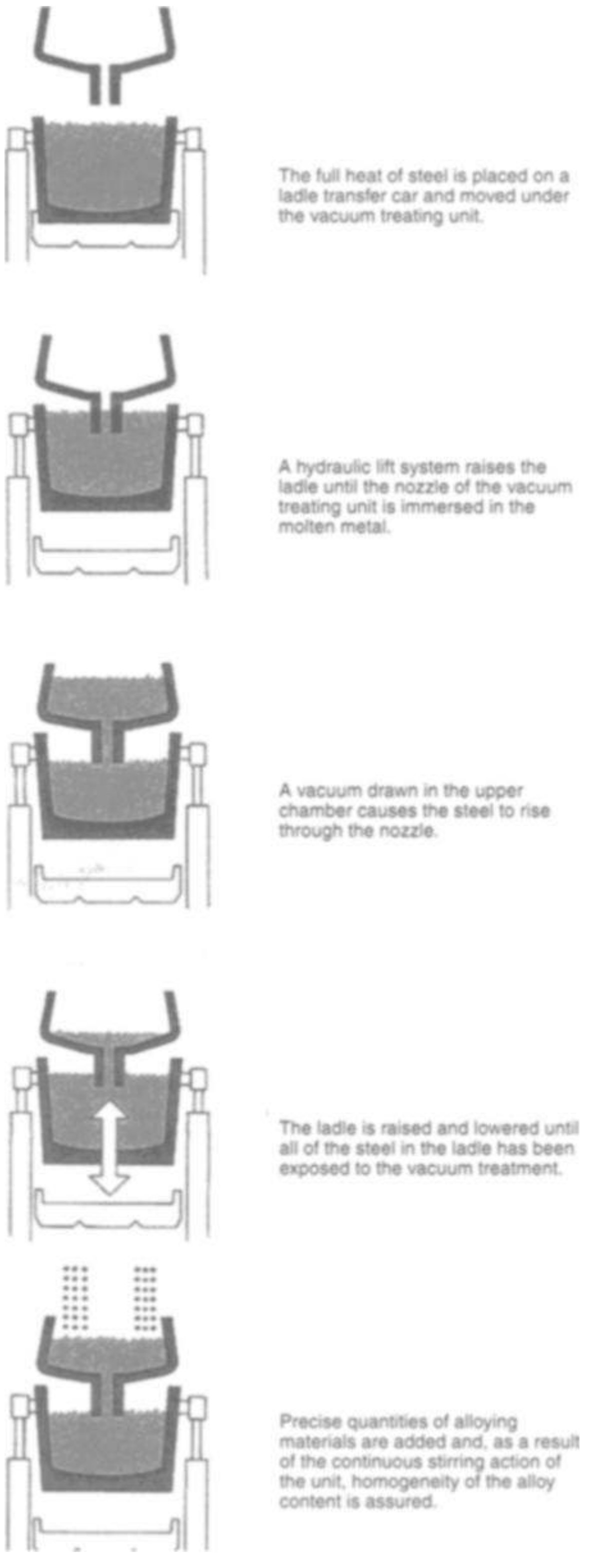


Fig. 3.2—Forty-five ton (41 t) Dortmund Hörder (DH) vacuum lift degassing unit in operation. The ladle is being raised or lowered in this view, but the nozzle (also known as a snorkel) always remains in the molten steel in the ladle under the slag cover during the entire degassing operation.

through a system of hoppers. The bottom of the vessel is conical in shape and ends in a refractory lined nozzle. The vessel is blanked off with a sheet steel cone before pulling a low vacuum similar to that in the stream degassing process. The furnace ladle is loaded into a cradle under the vacuum vessel, and the ladle is lifted hydraulically until the nozzle breaks through the slag layer and is immersed in the steel. The sheet metal cap prevents the slag cover from being drawn up into the vessel, and melts off in the ladle, permitting steel to be pushed up into the vessel under atmospheric pressure. The steel at this juncture is not fully killed, and under the low-pressure conditions existing in the vessel, is turbulent facilitating an effective degassing action. Some vacuum carbon deoxidation also occurs during degassing. While keeping the nozzle immersed in the steel, the ladle is lowered and then raised again circulating fresh steel from the ladle into the vacuum vessel. The process is continued until pressure surges in the vessel subside and a finishing pressure less than 1000 μm has been obtained. Toward the end of the degassing cycle the trim elements, particularly carbon and manganese, are added as well as deoxidizers such as ferrosilicon and grain refiners such as ferrovanadium or aluminum. Following these additions, several mixing strokes are administered to ensure uniformity. Although provided with a carbon arc near the top of the vessel for heating, a close watch has to be kept on the ladle temperature to ensure that the correct teeming temperature range for the grade of steel is maintained. At least 15 strokes are generally required for the full treatment of a 45-ton (41 t) heat. The vacuum carbon deoxidation that occurs during this procedure is not as efficient as that in the stream de-



The full heat of steel is placed on a ladle transfer car and moved under the vacuum treating unit.

A hydraulic lift system raises the ladle until the nozzle of the vacuum treating unit is immersed in the molten metal.

A vacuum drawn in the upper chamber causes the steel to rise through the nozzle.

The ladle is raised and lowered until all of the steel in the ladle has been exposed to the vacuum treatment.

Precise quantities of alloying materials are added and, as a result of the continuous stirring action of the unit, homogeneity of the alloy content is assured.

Fig. 3.3—Schematic of the operation of a DH vacuum degassing unit. A single cycle consists of raising and lowering the ladle. These cycles are repeated until a steady vacuum pressure indicates that degassing is complete. At the end of degassing, deoxidizers and trim carbon and alloying elements can be added under vacuum.

gassing process, and the maximum silicon is generally limited to 0.12 %.

Another vacuum lift degassing procedure is the Ruhrstahl-Heraeus (RH) system. This differs from the DH system in having two nozzles or legs that are immersed in the ladle. One leg is fitted with an argon inlet, and after being immersed in the slag covered ladle a vacuum is applied to the vessel, so that atmospheric pressure pushes the steel up both legs into the vessel. Argon is pumped into one leg and this effectively reduces the density of the steel in that leg, inducing a pumping action that causes the steel to circulate up one leg into the vessel and back into the ladle through the other. Through the action of the argon and turbulence in the vessel degassing is achieved under high vacuum conditions.

It should be noted that although a useful reduction in hydrogen content can be achieved during the AOD refining of alloy steels—this is due to the argon gas used in the process sweeping hydrogen out with it—such steels cannot be substituted when vacuum degassing is a mandatory specification requirement. Hydrogen levels in carbon and alloy steels produced in an AOD vessel are unlikely to be less than 2 ppm.

Steel Cleanliness and Inclusion Shape Control

Frequently, forging applications involve fatigue loading and for this steel cleanliness, or freedom from nonmetallic inclusions, is of paramount importance, since these can and do act as fatigue crack initiation sites. Reduction in the quantity of nonmetallic inclusions also assists materially in improving transverse ductility. This is particularly true when dealing with forgings that have received high forging reductions in the longitudinal direction, and where demanding transverse properties are required, as is the case for artillery gun barrels, for example. As part of clean steel production, particularly for the ordnance and power generation industries, it is necessary to reduce the sulfur content to levels appreciably less than 0.010 %, or in other words, well below the maximum limits allowed in many material specifications.

A steel making technique that is worthy of note for forgings is inclusion shape control. The object here is to have the inclusions adopt a spherical or globular habit instead of being strung out or elongated in the direction of working, as is typically the case for manganese sulfide. This is achieved by the introduction of an element such as calcium in powder or wire form into the ladle after deoxidation has been completed. The resulting inclusions resist deformation during forging and resemble (and would be rated as) globular oxides if the steel is examined according to ASTM E 45 Test Methods for Determining the Inclusion Content of Steel. This change effects a remarkable improvement in transverse ductility and toughness. In bar materials, particularly, this technique has been used to obtain a high degree of machinability while maintaining tensile ductility, by applying it to non-free-machining steels that have sulfur contents near to the permitted maximum. However, in this example the globular inclusions can be quite large and numerous. This may not be advisable for forgings that are subject to fatigue loading in service. A paper dealing with shape controlled sulfide free machining steels [6] noted that, provided the globular inclusion size was kept small, machinability and fatigue strength of engine rocker arms and crankshafts were equivalent to currently used leaded steels. However, it could be argued that leaded steels would not be selected for high fatigue strength. Another advantage claimed for inclusion shape control is that the outer coating of the globular sulfide inclusions affords a degree of lubricity to the cutting tool, increasing its useful life.

Steel cleanliness is the major factor in the incidence of laminations and lamellar tearing in plate steels. The ingot requirements, specification and application demands, and hot working procedures for forgings have meant, fortunately, that these problems are rarely encountered in this product form.

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4

Forging Ingots

IN THE EARLY DAYS OF THE MODERN STEEL industry, ingot teeming was done by top pouring into tapered cast iron molds for all applications. For rolled plate applications rectangular cross section molds were used. For bar and some strip applications the ingot molds were either square or round in shape, but for forgings the ingots were usually round or octagonal in cross section, and particularly for the larger sizes were almost invariably fluted to reduce the risk of surface cracking during solidification and subsequent cooling. A typical big end up, octagonal, top poured forging ingot from 1921 is shown in Fig. 2.14, and another modern 600-ton (545 t) ingot cropped and heated for forging is shown in Fig. 4.1.

Another important difference between forging ingots and those for plate or bar application is that for the latter the molds, for ease of stripping, are tapered to be smaller in cross section at the top, referred to as big-end down, while the forging ingots are tapered to be larger in cross section at the top, or big-end up. The forging ingots are fitted with insulated hot tops that act as feeder heads to fill the shrinkage pipe that forms as the ingot solidifies. This was often not done in the case of the big-end down molds.

Fig. 4.1—Six hundred-ton (544-t) alloy steel ingot that has been cropped and heated to forging temperature prior to being taken to the press. (Courtesy of The Japan Steel Works, Ltd.)

Most plate and bar mills now use continuous or strand casting machines as the link between steel making and rolling mill. In this process the steel is teemed from the ladle into a tundish from which it flows through a nozzle into an open-ended water-cooled copper mold. The rate of flow is timed such that the cast product exiting the mold has solidified sufficiently to contain the still molten core, and solidification continues under water sprays as the strand travels. The strand thus formed is guided through sets of rolls that maintain the strand shape before being cut into lengths. As previously mentioned, steel from these machines is also used for forging stock.

As well as the ladle refining processes discussed earlier, two other steel melting procedures must be mentioned for their importance in forging application. These are the Vacuum Arc Remelting (VAR) process and the Electroslag Remelting (ESR) process. The former has been augmented by coupling Vacuum Induction Melting (VIM) with subsequent VAR processing for extra critical applications. Material from the vacuum procedures in this group has been specified for demanding forging applications in the aerospace industry, such as aircraft landing gear, flap tracks, and arrestor hooks, not to mention many rotating components in aero engines.

Vacuum Arc Remelting

In the VAR process a cast electrode is produced in the conventional way, preferably from vacuum degassed electric furnace steel, together with the advantage of ladle refining or from a vacuum induction melted heat. This electrode is then arc melted in a water-cooled crucible under vacuum. A sketch illustrating the operating principles of a VAR furnace is included in ASTM A 604, Standard Test Method for Macroetch Testing of Consumable Electrode Remelted Steel, and is reproduced here (Fig. 4.2). The melting rate is carefully controlled to minimize segregation in the remelted ingot. As well as freedom from the adverse effects of dissolved gases, other benefits include the wide distribution of inclusions as the very fine globular oxide type. The quality of a VAR ingot is directly related to the original quality of the electrode, and there is no sulfur or phosphorous removal. During the VAR process there is a significant loss of manganese, drawn off as vapor, and this has to be allowed for in the chemistry of the electrode. It will be seen then that the composition of VAR steel must be determined from the remelted ingot, or the product from it, rather than the heat chemistry of the electrode. The specification requirements

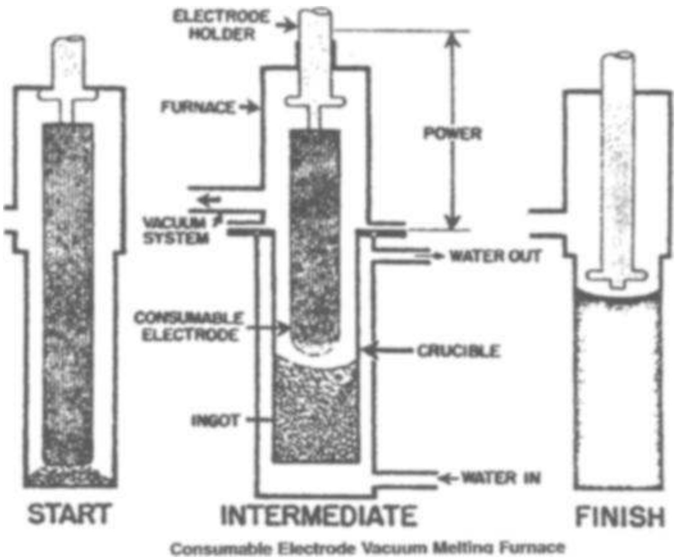

Fig. 4.2—Schematic of the operation of a vacuum arc remelting furnace from ASTM A 604, Standard Test Method for Macroetch Testing of Consumable Electrode Remelted Steel Bars and Billets.

for composition must be followed carefully when using remelted ingots, since commonly several electrodes are made from an original heat, and each remelted ingot represents a separate melting operation. Depending on the governing specification, it may be necessary to regard each remelted ingot from a common master heat as a separate heat requiring its own chemical analysis. In most other cases, it is only necessary to obtain the final chemistry from one of the remelted ingots from a master heat. For forging applications, the purchaser is always able to specify that a heat analysis is necessary from each remelted ingot. However, it should be remembered that the purchaser of VAR ingots will often be the forging producer; therefore, the forging purchaser must take note of the heat analysis requirements.

Electroslag Remelting

The ESR process had its origins in Russia and like the VAR process uses an electrode cast from an electric furnace heat. Unlike the VAR process, however, the electrode is not remelted under vacuum. For that reason, even when the product specification does not require vacuum degassing, the electrodes should be vacuum degassed. The melting takes place in a water-cooled crucible under a blanket of molten slag. A small electric furnace is provided at the remelting station to make the slag. Heat is generated because of the electrical resistance of the molten slag, and the electrode melts off with droplets of steel passing through the slag, collecting in a molten pool beneath it, and then solidifying. Sulfur removal is effected during this process, and as in the VAR process the residual inclusions have a globular shape that is retained during hot working. Since the operation is not carried out under vacuum, there is a high risk of hydrogen pickup during remelting, and elaborate precautions must be taken, such as ensuring that slag materials are dry. The provision of a dry air hood over the furnace to exclude moisture is another common measure for this purpose, and a closed ESR furnace design has been developed [1]. This encloses the ESR furnace and enables a dry inert atmosphere to be maintained during the remelting process. The development of a pressurized ESR furnace has facilitated the production of high nitrogen stainless steels [2].

Control of the slag composition is critical to avoid undesirable effects in the steel. In one instance, severe graphitization was reported in a high carbon ESR steel of near eutectoid composition, as a result of excessive aluminum pick up from the ESR slag. Again from ASTM A 604 a sketch (Fig. 4.3) gives some idea of the process.

Another application of ESR remelting is found in the practice of ESR hot topping a large conventional ingot, and is known as the Böhler Electroslag Topping process (BEST). The procedure involves teeming the steel conventionally into a cast iron mold fitted (instead of a conventional insulated hot top) with a water-cooled top ring. When the steel level in the mold reaches the bottom of the water-cooled ring, the ring is filled with a molten slag, and a consumable electrode is melted off through the slag, as in a conventional electroslag crucible. The infusion of heat and clean steel to the top of the teemed ingot significantly alters the solidification characteristics, and while feeding the solidification shrinkage in the ingot, it is claimed to reduce the ingot segregation [3]. Another variation in the use of ESR was developed for use in the manufacture of large rotor forgings [4]. This process for central zone remelting is known as the MKHW Process and is quite involved. A very large conventional vacuum

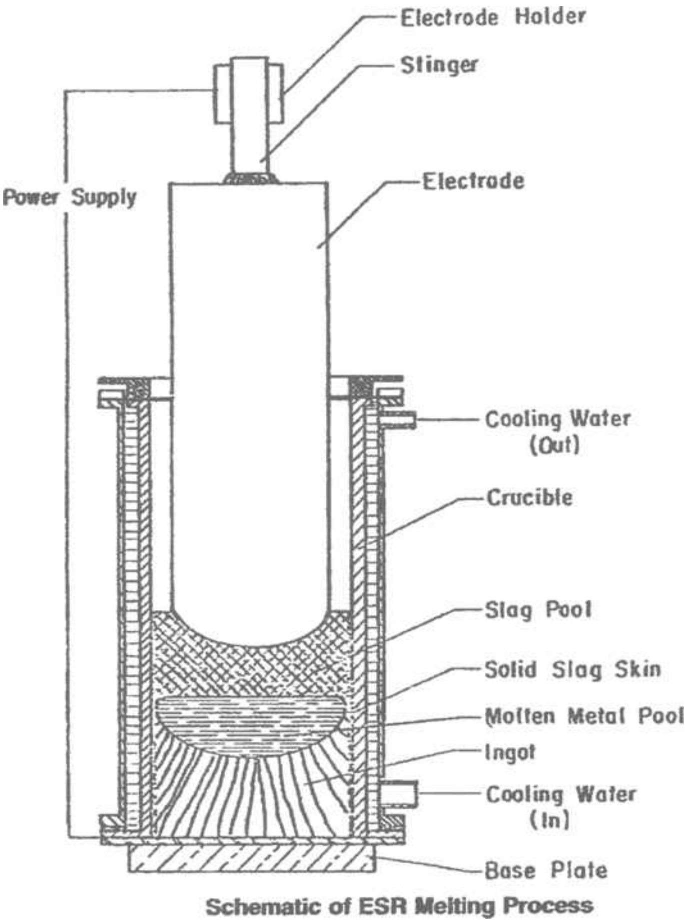

Fig. 4.3—Schematic of consumable electrode electroslag remelting (ESR) operation from ASTM Test Method A 604.

stream degassed ingot is prepared by taking the top and bottom discards followed by hot trepanning to remove the central segregated core. Using an electrode to the same specification and the trepanned ingot as the crucible, the electrode is remelted by the ESR process to replace the core material, and the new ingot is then forged in the usual way.

Another advantage in using ESR ingots is that the amount of forging reduction required is considerably less when compared to conventional ingots. Forging reductions as low as 1.5:1 have been reported to be acceptable [4].

Although steel from ESR furnaces showed some early promise for large critical power industry forgings, such as turbine and generator rotor forgings, low sulfur, ladle refined and vacuum degassed alloy steels have successfully challenged ESR material in terms of quality and cost in many applications. However, for the extremely large ingots used for critical rotating components, there may still be a place for specialized procedures such as the BEST process. Much the same can be said of the VAR process except for the most severe situations when the best VAR electrode and remelting practices can prevail. The VAR process is a requirement in some specifications, so that regardless of the quality obtainable from rival melting processes, this method must be used in making the final product.

Ingot Mold Design, Ingot Production and Segregation

As previously mentioned, forging ingots differ from those used in rolling plate and bar by being cast in molds that are of the "big end up" type. The "big end down" type of mold simplified handling by the ability to lift the open-ended design molds directly off the ingots. Although it might be expected that a big end down forging ingot could be lifted out of the mold, usually it has to be lifted together with the mold and inverted for stripping. Both styles can be fitted with hot tops or feeder heads to reduce the shrinkage voids or pipe that form when the ingot solidifies; however, often the big end down ingots are not treated this way. This is of great importance because of the size of ingots used for forgings that can range in weight from about 2 tons (1.8 t) to over 600 tons (545 t). Considerable investigation and development of ingot mold design, including computer modeling, has been done over the past 100 years, including a series of nine reports on the heterogeneity of steel ingots published by the British Iron and Steel Institute [5] between1926 and 1939. Much of this work was directed to rimming steel ingots, an important starting point for certain wire, strip, and sheet applications, but of lesser importance for forgings.

Alloy segregation [6] is an important topic for forging ingots, since this can have a profound effect on mechanical properties and weldability. The problem becomes more acute with increasing ingot size. In very large ingots where steel from more than one furnace is needed [7], the chemistry of the final heat that will essentially feed the top of the ingot and the hot top, or sinkhead as it is sometimes called, is adjusted to help compensate for alloy segregation effects. Nonmetallic inclusions tend also to segregate during ingot solidification, especially towards the top and bottom, giving rise to the so-called inverted "V" or "A" and "V" segregates, respectively. These areas are the locations for the top and bottom ingot discard material when making a forging.

For the larger top poured ingots, stools are frequently used for the ingot mold bottom, and the joint between the mold and the stool is sealed to avoid leakage at the joint [8]. The stools are replaceable and avoid erosive wear of the mold. However, some washing of the mold wall still occurs and this causes ingots to stick in the mold, and is one of the limiting factors in mold life.

Bottom pouring is now the preferred ingot teeming technique, except when vacuum stream degassing. Bottom pouring, as the name suggests, involves setting the molds onto a steel plate fitted with radially disposed grooves or channels around a central refractory lined stem called a sprue that fits into a ceramic distributor block. The channels in the plate are lined with disposable refractory tubes that fit into the distributor block and end in elbows under each mold. The ingot molds are set on the plate over the refractory tube elbow outlets, and steel is teemed from the ladle into the sprue until the ingots have been filled. Bags of a glass-like flux material are hung in the molds, and these burst as the steel enters the molds so that a molten glass flows up between the steel and the mold wall, and protects the steel as well as the mold. Importantly, this also imparts a very smooth skin to the ingot. An insulating compound, such as vermiculite, is thrown on top of the ingot when pouring has finished. Because of the close proximity of the ladle nozzle to the top of the sprue, it is possible to shroud the molten stream effectively with argon. This helps reduce reoxidation during teeming with beneficial effects on the nonmetallic inclusion content. Two VAR electrode molds are shown in Fig. 4.4 just after teeming, with the hot tops in place.

Radical ingot designs have been proposed and produced in France by Creusot Loire Industrie [9] for large forging applications. These include long ingots for forged vessel shells and short stubby ingots for vessel heads and hollow ingots also for vessel shells. All of these ingots have been designed with an eye to locating segregated areas in locations where they will be removed either during forging or by subsequent machining, or where, in the case of the hollow ingots they will be confined away from highly stressed areas or where weld overlays will be applied. The term LSD meaning "Lingot a Solidification Dirigee" or "oriented solidification ingot," rather than English terminology, is used to describe these ingots.

Forging Stock

Traditionally, cast ingots constituted the basis for forging stock, particularly for larger sized forgings that matched the available ingot weights. For smaller forgings and for forging producers operating drop hammers and closed die presses, the use of wrought billets or blooms is common. The term "bloom" as applied to wrought iron or steel appears to predate billet, since in medieval times the "Bloomery" included the iron or steel making furnace and the forge [10].

Billets are generally regarded as being smaller than blooms, and Specification A 711/A 711M for Steel Forging Stock defines a billet as having a maximum cross-sectional area of 36 in.^{2} (230 mm^2) and a bloom as having a cross-sectional area greater than 36 in.^{2} (230 mm^2). However, these terms are used interchangeably, and this is noted in the terminology section of Specification A 788.

As mentioned earlier, billets and blooms for forging stock are expected to have been hot worked by forging or

Fig. 4.4—Thirty-seven-in. (940-mm) VAR electrodes immediately after bottom pouring. The sprue pipe is visible between the molds. The hot tops for the electrodes are topped by the flux that was originally suspended in the molds from the rods lying across the hot tops.

rolling, and this prior working was often taken into account in determining the amount of hot working reduction that needs to be done in making the finished forging, particularly for closed die forgings. This may not be the case for stock that was strand cast, and this is noted in Specification A 788, with the requirement that this material must be designated as a "Cast Billet" or a "Cast Bloom."

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5

Types of Forging

FORGINGS ARE CLASSIFIED ACCORDING TO THE production method and fall into five major headings: Open Die; Closed or Impression Die; Rotary, Ring Rolling, and Extrusion. Further subdivision comes from the types of equipment used to make the forgings: Hammer (steam, hydraulic, or mechanical); Press (steam, hydraulic, multi-directional, or mechanical). For some specialized applications the boundary between open and closed die forging can be blurred as in the use of split dies for valve body manufacture or in the manufacture of wrought locomotive and rail rolling stock wheels.

Open Die Forging

Open die forgings [1] are free form worked between two dies, the lower of which is generally fixed. The movable die may be the tup of a hammer or an attachment to a hydraulic ram in a press. The normal forging dies are flat rectangular shapes, and are frequently water-cooled. For special forging applications, such as mandrel forging, the bottom die is changed to a V shape. Occasionally, both top and bottom V dies are used, and for finishing planishing or swaging operations curved top and bottom dies can be employed. The material to be forged, in the form of a heated ingot, bloom, or billet, is compressed between the dies and reduced in cross-sectional area. Nowadays, the material is held by a manipulator, either rail-bound or free running, so that it can be moved back and forth between the dies and rotated as necessary. A tong hold has to be provided for this purpose, and the ingot hot top is useful for this. For quite small pieces, the forge-smith can handle the part manually using tongs. In the early days when forging the larger pieces, a porter bar was used as depicted in James Nasmyth's painting of 1871 (Fig. 1.5). The porter bar consists of a long steel bar fitted with a cup at one end. The top of the ingot fits into the cup and making use of leverage the hot ingot can be maneuvered manually between the hammer dies by the forge crew. Since only the material under the dies is worked at any given moment, it is possible to forge very long pieces with this type of equipment, and the maximum forging diameter is limited only by the dimensions and power of the press, as well as the available ingot sizes. Therefore, the width between columns, and maximum opening between the dies, or press daylight, are important factors, together with available power, in assessing a forging press. With the appropriate tooling and die changes, open die hammers and presses can produce disk shaped parts and hollow cylinders. This type of equipment is versatile and ideal for many forging applications. Forging hammers are usually of the single acting type where the hammer or tup is raised under power, and allowed to drop under gravity. Some double acting steam hammers increase the forging force by pushing the hammer down under steam pressure, to give an intermediate effect between drop hammers and steam or hydraulic presses; the latter by being able to exert a more continuous force are more capable of properly working thick sections.

Open die forging operations under a hammer or press can be classified under six headings as follows:

- *Straight or Axial Forging*: In this the material is extended axially to reduce the cross-sectional area and increase the length, as in forging a ship's propeller shaft, for example. The working is said to be longitudinal and ductility will tend to be higher parallel to the direction of working than in the transverse direction. The flat top and bottom dies are oriented at right angles to the longitudinal axis of the forging, as shown in Fig. 5.1.
- *Upset Forging:* The ingot or billet is compressed axially under the press, as shown in Fig. 5.2, and the length or height is reduced while the diameter increases. Transverse ductility properties are improved over the axial properties. The ingot or billet is compressed between top and bottom plates that are larger in diameter than the ingot.
- *Hot Trepanning or Hot Punching*: An axially oriented hole is hot trepanned from the upset forging using hollow steel cutters to remove the segregated ingot core and provide for further hot working. Hot punching is a similar operation, except that instead of removing the ingot core, the material is pushed into the wall of the upset forging. A thin disk is usually pushed out at the end of this operation. An example of hot trepanning is shown in Fig. 5.3.
- *Ring Rolling or Expanding*: This operation expands the bore of the trepanned or punched upset forging on an open die press, while maintaining the axial length of the piece, as opposed to making steel rings on a dedicated ring-rolling machine that employs powered rollers. The flat top die is turned 90° to the axial direction and the piece is hot worked between the top die and a mandrel bar, smaller in diameter than the forging bore and supported on horses on each side of the ring, as shown in Fig. 5.4. The wall thickness is reduced as the diameter is increased. This may be the finished shape of the forging, or it could be a preparatory stage in opening the bore to fit a steel mandrel for increasing the length of the hollow forging. The mechanical properties will tend to be highest in the tangential orientation of the ring. Rings forged in this way are generally too large for conventional ring-rolling machines. Several descriptions of the equipment used to make forged rings and the products produced including the very specialized generator retaining rings have been published [2–4].
- *Mandrel or Hollow Forging*: The hollow cylinder is fitted over a water-cooled tapered mandrel and forged between the flat top die and a V-shaped bottom die to re-

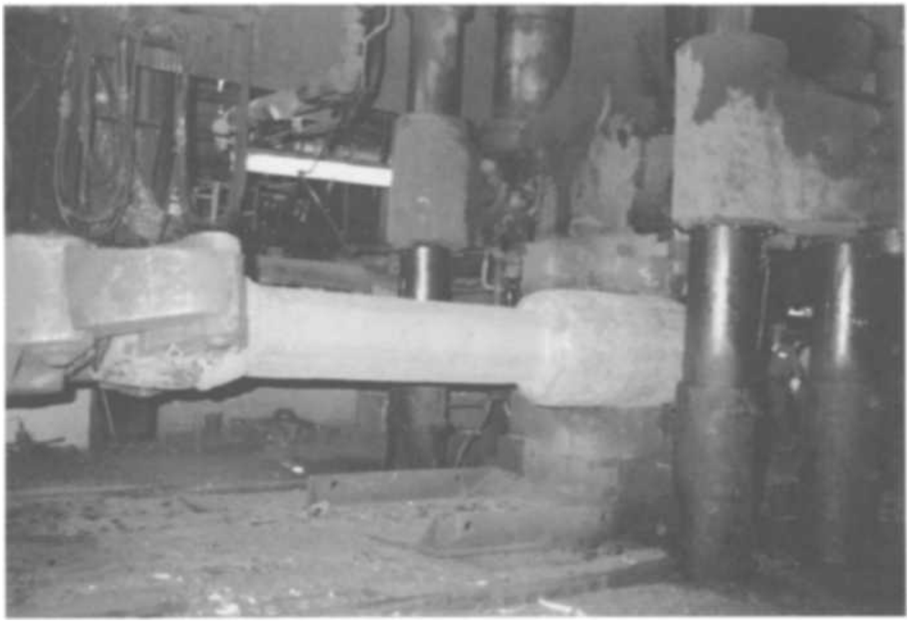

Fig. 5.1—Example of straight forging in a 3.5 Ni-Cr-Mo-V alloy steel according to ASTM A 723. This was the completion of the forging shown being upset in Fig. 5.2, and was part of the anchor system for a tension leg platform (TLP) in the North Sea.

duce the wall thickness and extend the length of the cylinder, as shown in Fig. 5.5. It is possible to forge different outside diameters during this operation. Depending on the degree of the initial upsetting operation, bore expansion, and finished length, the mechanical properties in the finished forging can be essentially isotropic.

Pancake or Disk Forging: This is an extension of upset forging in which the upsetting operation is continued to increase the forging diameter and decrease its thickness. Depending on the forging size and press capacity, the later stages may be completed by "knifing" across the forging diameter using the flat top die, and turning the forging over to work both sides. For very large diameter disks that exceed the width between the press columns, special equipment may be used to permit only a part of the disk at a time to be worked under the dies. An example of this is shown in Fig. 5.6. The mechanical properties of the disk tend to be best in the tangential and radial directions, but will still be acceptable in the axial direction.

Closed Die Forging

In closed or impression die forging, the starting forging stock is invariably a billet or bloom, since the weight and dimensions are usually critical. Upper and lower dies are contoured or sunk to form the required shape when the billet is inserted between them. The forging force may be supplied instantaneously, as in drop forging, when the dies are closed over the billet, or more gradually when a hydraulic press is used. High forging pressures are required to make the material flow to fill the dies, and for even modestly sized forgings such as automotive crankshafts, hydraulic or large mechanical presses are generally used. Since appreciable costs are involved in providing the dies, closed die forging is more applicable to large production runs, but the advantages are reflected in much reduced or, in some cases, no machining, and favorable grain flow. Die lubrication is essential and involves the use of a material such as colloidal graphite or molybdenum disulfide. For the more complex forged shapes, the billet is preforged in an intermediate set of dies, often referred to as blocker dies, before forging between the final dies. ASTM Specification A 521/A 521M, Steel, Closed-Impression Die Forgings, for General Industrial Use, addresses this type of forging. A variation of closed die forging involves the use of special equipment, either as a multidirectional hydraulic press or as a system of levers and dies used in conjunction with a conventional open die press. This will be discussed later in connection with crankshaft forging.

Extrusions

Extrusion presses work by forcing material, contained in a cylinder, through a die or orifice. In the case of steel extrusions, the steel is preheated to forging temperature before being loaded into the extrusion press.

In *Direct Extrusion* the steel is pushed, from behind, through a contoured die placed at the end of the container opposite to the piston.

In *Indirect Extrusion* the steel is pushed so that it flows back through both the die and the piston that is applying pressure.

In *Back Extrusion* the heated steel preform is forced back through the annular space between the piston and the walls of the containing cylinder. This method produces items as diverse as heavy walled steel pipe and blind-ended vessels.

Die lubricants such as colloidal graphite are an essential part of steel extrusion.

In steel extrusion, particularly for shapes such as channels and "H" sections, the structure of the product as extruded can exhibit some variation from start to finish, since

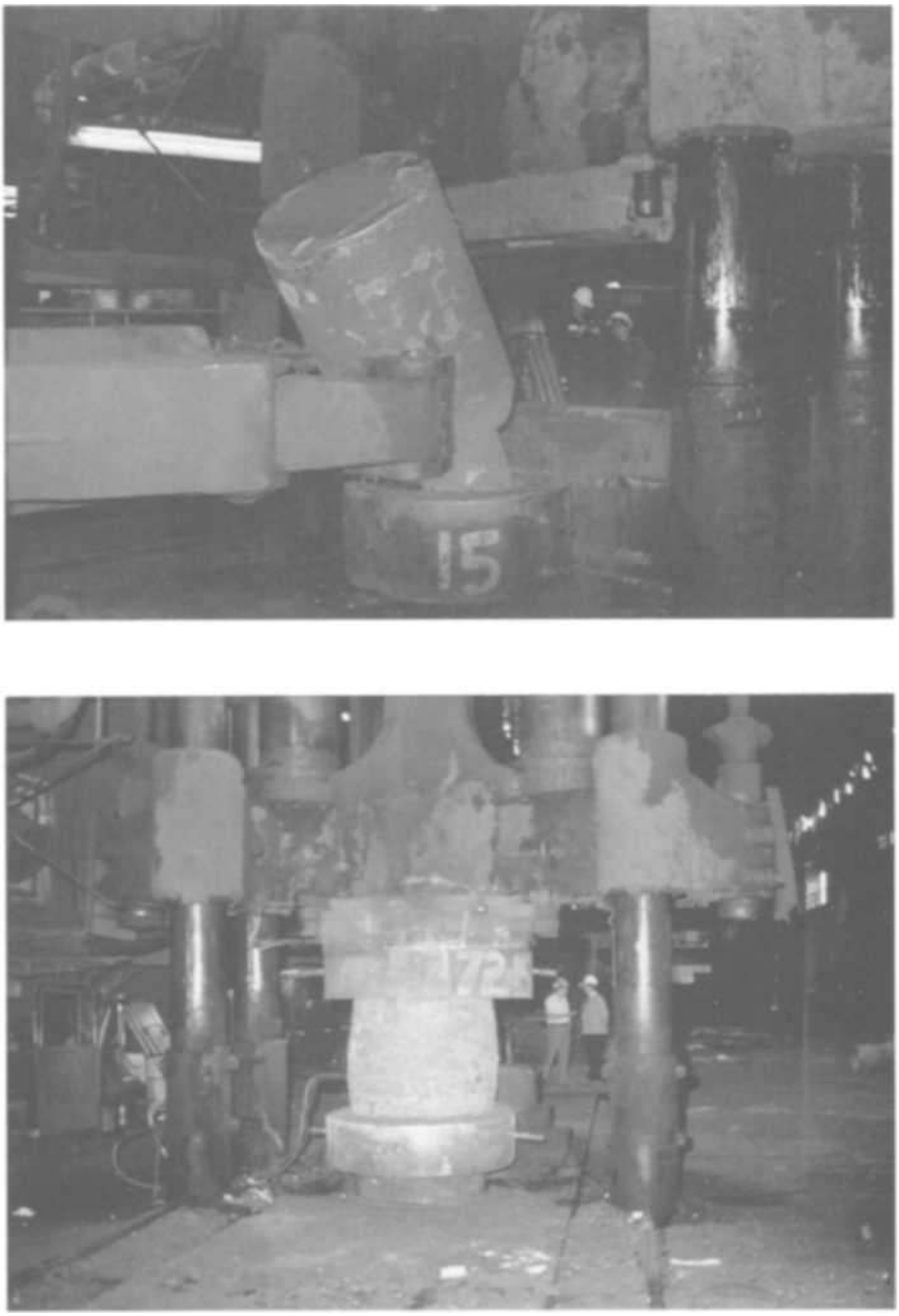

Fig. 5.2—Stages in the upsetting of a 40-in. (1000-mm) VAR alloy steel ingot. In the top picture the previously prepared tong hold is inserted in the bottom pot die, and in the lower picture, near the end of the upsetting operation the forging has attained the characteristic barrel shape.

the first product to emerge will have been worked at an appreciably higher temperature compared to the end material as the steel cools in the extrusion chamber.

The extrusion containers are frequently multiwalled alloy steel forging assemblies that are set up in the extrusion press, together with any necessary stems and mandrels, as shown in Fig. 2.11.

Rotary Forging Machines

Rotary forging machines, Fig. 5.7, are designed to produce bars quickly by passing a rotating heated billet under multiple hammers that beat the material, reducing the cross-sectional area and increasing the length. The hammers are synchronized and work rapidly over a relatively short stroke. Figure 5.8 demonstrates a typical hammer arrangement. Surface finishes are possible that closely rival good rolled finishes. These machines usually have numeric controls and can produce rectangular shapes. Hollow sections can be produced also by forging over a mandrel: for example, 120-mm tank cannon tubes, tapered from breech to muzzle, can be produced in one operation from preforged and bored blanks using this type of equipment. Figure 5.9 illustrates the use of mandrels for hollow forgings.

Fig. 5.3—Hot trepanning the upset forging removes the segregated central core, a preparatory step to forging over a mandrel to expand the bore, or to reduce the wall thickness and increase the length of the forging. (Courtesy of The Japan Steel Works, Ltd.)

Cold forging and swaging of automotive drive train components on rotary forging/swaging machines can produce some complex configurations, as shown in Fig. 5.10.

Technical descriptions of the operation and use of radial forging machines have been presented at meetings of the International Forgemasters [5, 6].

Ring Rolling

Ring-rolling machines are used to produce a variety of seamless forged rings that can vary greatly in diameter, but are restricted in axial length. An upset forged disk blank is prepared by heating into the forging temperature range and is then punched in a press to produce a thick walled ring. This is then moved to the ring-rolling machine and placed between the two powered roller dies. The gap between these dies is steadily reduced, pinching the blank and reducing the wall thickness as the ring passes between them. The axial length of the ring is constrained and the diameter increases as the wall thickness is reduced. Large ring-rolling machines are shown in Fig. 5.11. Following the ring-rolling operation the post forge treatment, as in the case of open die and closed die forgings, depends on the steel composition.

Fig. 5.4—Once bored, the upset forging can be expanded on an open die press by forging between a special axially oriented top die and a mandrel bar that is rests on supports at each end of the forging. The bottom press die does not come into play and is moved out of the way. The forging is rotated during this operation in which the axial length remains constant, but the diameter increases and the forging wall thickness is reduced. (Courtesy of The Japan Steel Works, Ltd.)

Forging Reduction

An important criterion for making forgings is the degree of hot working that goes into transforming the ingot material into the forged product. This is measured as a Reduction Ratio obtained by dividing the original ingot cross-sectional area by the maximum cross-sectional area of the forging. Expressed as a requirement, this can vary appreciably depending on the application, but a forging reduction ratio of 3:1 is commonly used. In the case of a hot worked billet or bloom, a minimum reduction ratio of 2:1 is not uncommon; and particularly when making closed die forgings, this may be increased to 3:1 since parts of the finished forging may see very little further work in the final shaping operation. In making very long forgings, such as marine propeller shafting, reduction ratios could well be as high as 20:1 because of the large size of the ingot required to make the part. While maximizing the properties in the axial (longitudinal) direction, this degree of forging work tends to reduce the trans-

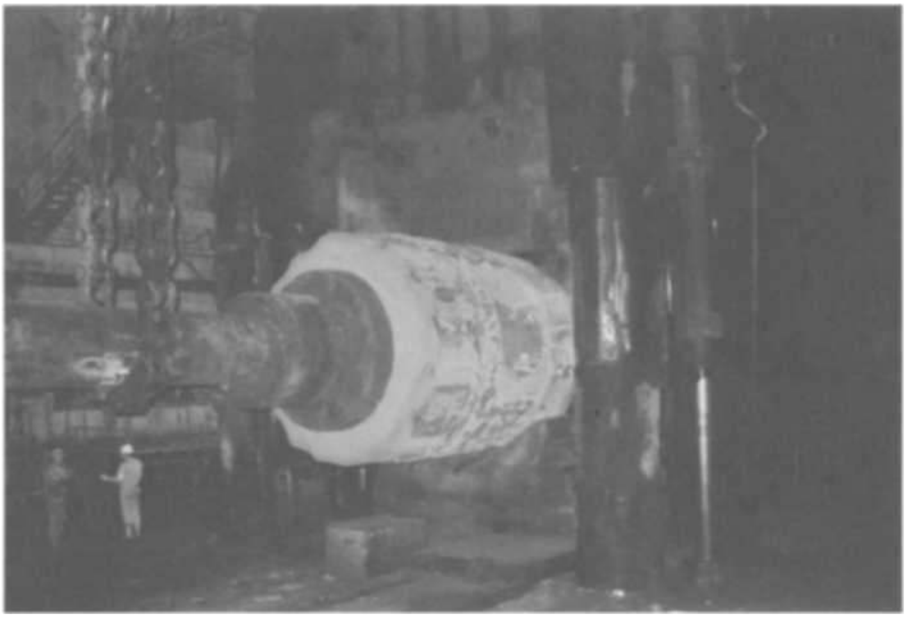

Fig. 5.5—When the required bore diameter has been obtained by the procedures shown in Fig. 5.4, the forging length can be increased and the OD contoured as necessary by fitting a water cooled tapered mandrel into the bore and forging between the normal transverse top die and a bottom Vee shaped die as illustrated. (Courtesy of The Japan Steel Works, Ltd.)

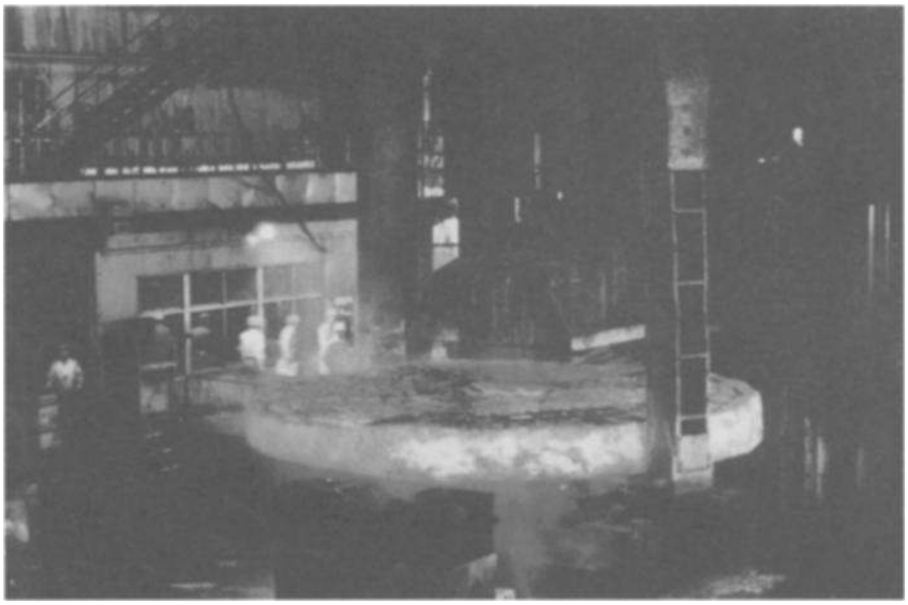

Fig. 5.6—For large diameter relatively thin components such as tube sheets, the upsetting process is continued, increasing the diameter as the thickness decreases. The width between the press columns is a limiting factor in this, but with special equipment to enable the forging to be rotated and a reinforced top die the forging can continue outside of the press columns as shown. (Courtesy of The Japan Steel Works, Ltd.)

verse ductility. Use of clean steel technology, however, will minimize this effect.

Increasing the diameter of the forging stock can be achieved by upsetting it, and this is an essential stage in the manufacture of several critical forged components, such as turbine and generator rotors. The billet/bloom, or in some cases the starting ingot, is compressed, increasing its diameter and reducing the length. The degree of upsetting is based on the ratio of the starting length to the finished length; thus, when the length is reduced by half the upset ratio is said to be 2:1. This is the common aim for an upsetting operation. A ratio of about 3:1 is considered to be the practical limit for upsetting, since there is a tendency for a long column to buckle as it is compressed. Direct upsetting of ingots is generally restricted to ingot diameters of 30 in. (750 mm) or less, largely because of lack of central consoli-

Fig. 5.7—Typical radial rotary forging machine in operation. The feed stock could be as-cast billets, wrought bar, or bored performs. (Courtesy American GFM Corporation)

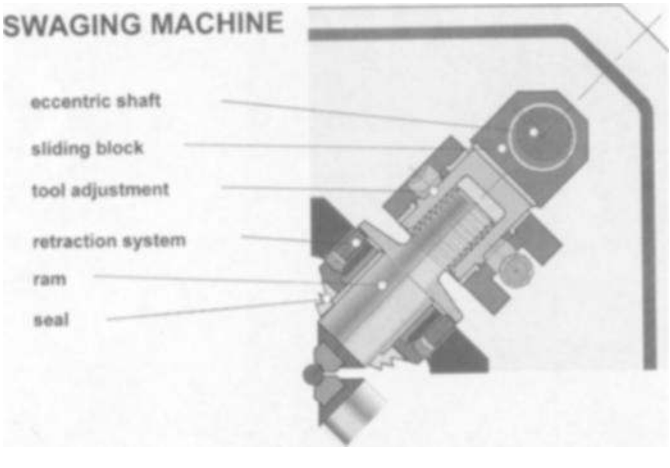

Fig. 5.8—Sketch of the hammer arrangement and drive in a radial rotary forging machine. (Courtesy American GFM Corporation)

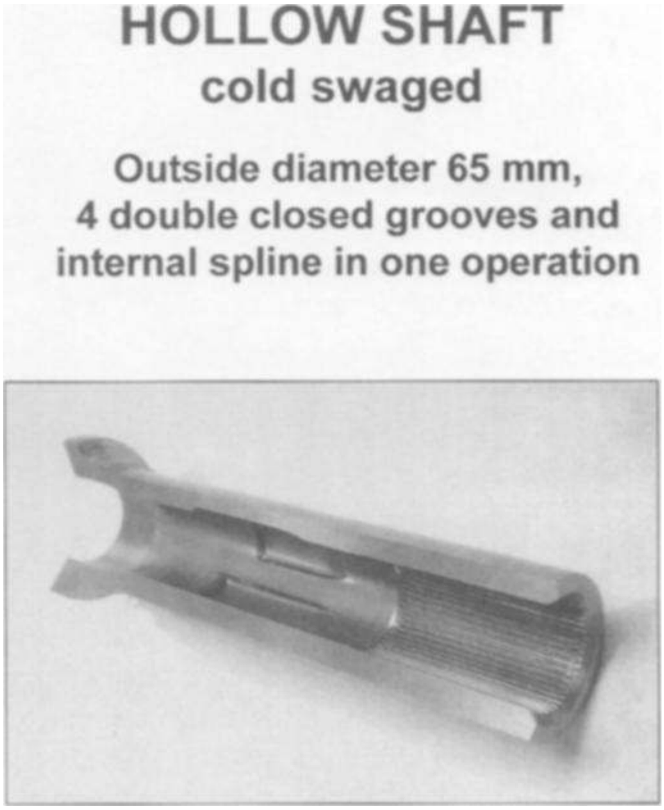

Fig. 5.10—Example of a small, hollow cold forged automotive component produced on a radial rotary forging machine and sectioned to show the internal configuration. (Courtesy American GFM Corporation)

dation. The more usual course is for the ingot to be forged axially (saddened) first to achieve a reduction of about 1.5–2 : 1. The forging is then trimmed to remove the hot top and bottom discards (thereby reducing the length) and is reheated for the upsetting operation. Because of the buckling risk, it is important that the ends of the forging be as square as possible before starting the upset. Lengthening the bloom during the ingot saddening procedure means that larger diameter stubby ingots are needed for items like tube sheets, rather than long slender ingots, in order to avoid buckling problems during upsetting. The available press power is an important factor in upsetting, since the resistance of the forging to compression obviously increases as the diameter increases. For this reason reserve power for heavy upsetting operations is sometimes built into the press. The available

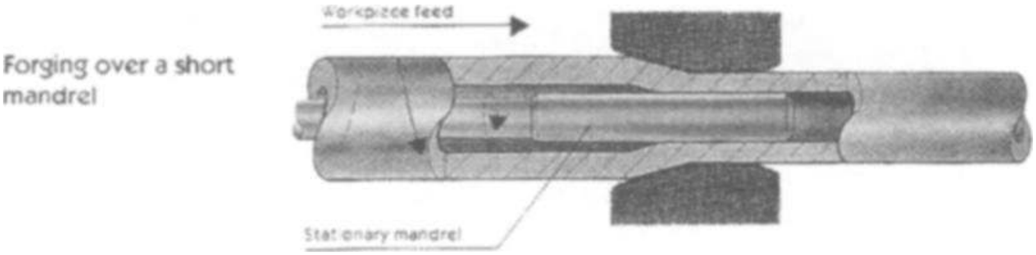

Fig. 5.9—Use of a rotating mandrel for hollow forging in a rotary forging machine. (Courtesy American GFM Corporation)

Fig. 5.11—Examples of large ring rolling machines. The upper picture shows a mill capable of producing rings with an OD up to 23 ft (7 m). The radial power is 800 tons (725 t) and the axial power 500 tons (45 t). The lower picture taken from the control room of a modern ring rolling mill gives an impression of how such operations economize on manpower. In this example the maximum radial power is 1000 tons (907 t) and the axial power is 500 tons (45 t). A tapered gear ring is being forged. (Courtesy SMS Eumuco Wagner Banning, Witten, Germany)

daylight, that is the maximum opening between the dies, is also another factor in the upsetting capability. For a large piece that approaches the limits of the press, when the upset is partially completed it is sometimes necessary to resort to a "knifing operation" to finish it. In this the large circular top upsetting die plate is removed and the normal rectangular die is used to forge across the top of the upset cylinder and gradually increase the upset. Ideally, the completed upset blank should have a distinct barrel shape.

For hollow cylindrical forgings or large rings, a hot trepanning or punching operation would follow the upset, and this may be done without the need for an intermediate reheating operation. For a solid forging such as a rotor, a tong hold would be necessary to facilitate drawing the forging back to size and forming any necessary journals. In this case the tong hold generally is made before the upset, and it is accommodated in a top or bottom pot die during the upset, as shown in Fig. 5.2.

The upsetting operation, by increasing the diameter, enables a higher longitudinal reduction ratio to be obtained than would have been the case from the original ingot or billet.

For disk shaped forgings, such as turbine wheels or tube sheets, the upsetting operation is continued to obtain the required diameter and thickness. This is sometimes referred to as pancaking. In Fig. 5.6 this final stage is shown being done outside of the press columns.

Unless the original stock, be it ingot or billet, has received sufficient axial working (saddening) before upsetting, central looseness or voids may make the forging unacceptable unless a sizeable bore is a part of the design.

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6

Heating for Forging

FORGING CREWS SOMETIMES SEEM TO WORK according to the "Hotter is Better" maxim, possibly because the steel may appear to move more easily, and the reduction in forging time can lead to greater financial rewards; however, as explained here the choice of forging temperature must be approached carefully.

A vitally important stage prior to forging is heating the ingot, bloom, or billet to forging temperature. The appropriate forging temperature will vary somewhat, depending on the type of steel involved and the hot working that has to be done. By definition, hot working is started above the recrystallization temperature for the steel, and it is desirable to finish hot working close to this temperature. For most steels, the power needed for hot working a given section size decreases with increasing temperature. Time taken to do the forging work can be reduced also when the work is heated to higher temperatures. There is an upper limit, of course, to the forging temperature that can be used before serious and even permanent damage is done to the material. This begins as excessive grain growth and then as incipient grain boundary melting and oxidation. Care, therefore, must be exercised not only in specifying the forging temperature, but also in the design, maintenance, and use of the heating equipment. This subject is dealt with in more detail in Chapter 13.

Heat to Forge Furnaces

Forge heating furnaces are frequently natural gas fired, car bottom batch furnaces, operating under a slight positive pressure, and designed to avoid flame impingement on the work pieces. This may be accomplished with burners arranged along the side walls, such that one row fires under the furnace charge—accomplished by the use of transverse bolsters laid across the car bottom—while on the opposite wall the burners fire over the charge. This arrangement provides for circulation of the combustion gases. The furnace temperature is controlled by dividing the working space into horizontal zones, each of which is fitted with control and check thermocouples that are set close to the top of the furnace charge. The control thermocouples regulate the heat input from the burners assigned to them, and the check thermocouples provide back up information, useful in diagnosing problems.

The zone temperatures are recorded on a chart. Computerized controls are available to cover the ramp up to the forging temperature, as well as the soak time at temperature. Good housekeeping is important to avoid excessive scale build up on the furnace car that could interfere with gas circulation within the furnace. Generally, several forge heating furnaces are required to permit the loading of ingots freshly stripped from the ingot molds into a relatively cool furnace before being brought up to forging heat, while other ingots are being forged and still others are in the heating process. This is necessary to allow for efficient use of the forging equipment. The use of mineral wool insulation pads rather than fireclay bricks for furnace insulation does enable more rapid cool down on completion of a forging run. The furnace car is moved out of the furnace so that the ingots can be removed by means of tongs operated from a crane, or by a mobile manipulator, and taken to the press for working. Overloading the furnace frequently leads to uneven temperature distribution and may sometimes be the cause of localized flame impingement.

Batch furnaces with stationary hearths can be used for forge heating. However, removing the ingots from these requires the use of a manipulator, or a porter bar through the furnace door.

For some forging operations, such as preparing a slab-forged crankshaft for twisting, heating is done in temporary gas fired furnaces built around the area to be heated. Temperature control is much more difficult in these situations, but very high temperatures may not be required if the amount of work to be done is slight. This type of heating is sometimes used for forge repairs.

The need to supply properly heated stock to the forging equipment in a timely manner is of great importance to the economic running of a forging operation. This need has spurred the development of continuous furnaces, such as the rotary hearth units, especially for smaller closed die operations.

While enough time has to be allowed at forging temperature for the temperature in the ingot or billet to equalize through the section (this also permits some coring or segregation effects from solidification to equalize also), it must be remembered that grain growth is occurring as well, together with decarburization and scaling. Fifteen to 30 minutes per inch of ingot or billet cross section is generally regarded as adequate for this purpose. Holding work at forging temperature for excessive times, perhaps because of equipment or scheduling problems, must be discouraged. In such situations, the furnace temperature should be reduced within the austenitic range, until it is possible to proceed with forging.

In some steel mill operations, when rolled bar and strip are the principal products, heating for hot working is done in some type of soaking pit. While, no doubt, some soaking pit designs are capable of good temperature control, some are little more than top loaded refractory lined chambers fitted with a single large burner placed in one wall, set so as to fire over the top of the charge. The flue is set lower, in the same wall as the burner, and a thermocouple is set beneath the burner. Temperature control of the charge in such facilities is tenuous at best, and uniform heating can be dubious. They are not recommended for forging applications.

Because forging furnaces operate at high temperatures, a great deal of waste heat is involved. Considering flue gas outlet temperatures in the range of 2100°F to 2350°F (1150°C to 1290°C), and the cost of natural gas, heat recovery by means of recuperative burners or waste heat boilers is an economic option.

Reheating

It is not uncommon for a partially completed forging to be reheated before proceeding to the next step. For example, when upsetting is required, the ingot may first be heated to 2200°F (1200°C) for the initial saddening, then reheated to 2350°F (1290°C) for upsetting, and then to 2150°F (1180°C) for finishing. The temperatures chosen should be considered with care, remembering to avoid possible overheating at the higher temperatures, and choosing the final temperature with a view to finishing the forging at a low temperature, in most cases appreciably lower than 1700°F (925°C) to avoid having an excessively coarse grain size.

Sometimes, a forging has to be reheated for completion, but is now too long to fit in a furnace. Heating the unfinished end of the forging in this circumstance must be approached gingerly, to avoid the onset of problems such as flake in the finished part, which should be insulated to control cooling until the forging can be completed. The use of vacuum degassed steel does help to minimize the risks in such a circumstance.

Planning of the forging steps is also important to avoid a situation where a reheat is necessary to complete only one part of the forging, such as a journal of a rotor, since this would mean reheating the whole forging, most of which would see no further hot working. Grain coarsening from this circumstance might be difficult to correct.

Induction Heating

For many repetitive forging operations, particularly those involving closed die forging, induction heating is an attractive option for the heat to forge part of the cycle. Induction heating is clean and fast, the equipment is compact, and the system is well suited to automated material handling systems. The induction heating furnace includes a water cooled copper coil sized to suit the billet being heated—one of the disadvantages of the method is that a given coil can only accept a billet cross section within fairly closely defined size limits, and the billet cannot be allowed to touch the coil. Low frequency power sources are used for forge heating applications, as opposed to high frequency units used for surface hardening operations.

Resistance heating results from the currents generated in the workpiece by the induction coil, and the temperature rise is rapid in the outer fibers of the material. The depth of heating in the workpiece from electrical resistance is limited to about 2 in. (50 mm), and the deeper-seated material towards the center is heated by conduction. Therefore, time for this to happen in the thicker billets must be allowed, but it has to be remembered that the temperature of the outside of the part will continue to rise as long as current flows in the coil. For sections over about 4 in. (100 mm) in diameter, therefore, a soak period with little or no power applied may have to be allocated. The importance of temperature control in induction heating cannot be overstated. The temperature reached in the billet is a function of the billet size and the electrical power input in terms of kilowatts. The temperature of the billet entering the furnace must be taken into account also, since this will affect the final temperature after a given power input.

Temperature measurement is generally done using an optical pyrometer system, such as Ircon tubes; however, these must be positioned to read the surface temperature in the furnace, or immediately after the piece leaves it, in order to minimize the effects of scaling. Surface scale tends to cool rapidly and can give misleading indications of low temperatures. While billet overheating is the major risk associated with induction heating, problems such as not filling the dies properly or internal bursts may be encountered through not allowing time for heat transfer through the section by conduction.

7

Post Forge Practices

ONCE FORGING IS COMPLETE, THE QUESTION OF handling the part must be considered. Generally, except for the austenitic stainless steels, before the part is allowed to cool and transform, several factors have to be taken into account. These include the type of steel used, whether or not vacuum degassing was employed in making it, the size of the forging, and the type of post forge heat treatment, if any that the part will be given.

Austenitic stainless steel forgings are generally permitted to cool in air after completion of forging, unless they are small enough for a direct solution-annealing quench from the forging temperature. However, this implies a high finishing temperature, since the required solution treatment temperature will be upwards of 1900°F (1040°C). Some product specifications will permit this practice, provided that the finishing temperature for forging was higher than the minimum solution treatment temperature for the grade of steel involved. This saves the expense of a separate solution annealing treatment downstream in the manufacturing sequence. The specification requirements in this regard must be watched, however, since some do not allow the practice at all and some prohibit it for grades intended for use at elevated temperatures such as the "H" grades. This is especially true for forgings that will be used under the ASME Boiler and Pressure Vessel Code.

The ferritic forgings must be permitted to transform on cooling after forging, but there are dangers in doing this. Bearing in mind that flake can only occur after an incubation period following the austenite transformation, it follows that the post forge cycle must allow this transformation to occur safely. Prior to the introduction of vacuum degassing, this often involved controlled cooling of the forging below the lower critical temperature, perhaps in a furnace, under an insulated hood or under a refractory insulating medium. This was then followed by an extended subcritical heat treatment cycle designed to facilitate the diffusion of hydrogen from within the part. This cycle was frequently very long, running for many hours per inch of cross-sectional area, so that for a large forging in a nickel-chromium-molybdenum alloy steel such as SAE 4340, about two weeks could elapse before the forging would be ready for further processing. Sometimes the cycle would involve reaustenitizing the forging to refine the microstructure before embarking on the subcritical part of the cycle.

Vacuum degassing of the steel significantly simplifies the post forge handling by reducing the risk of flake, and for many grades it is possible to forego the flake heat treatment cycle and simply cool in still air and proceed with the rest of the processing. Since flake can affect carbon as well as alloy steels, this was a very significant improvement. However, vigilance must be maintained on the vacuum degassing operation during steel making, ensuring that only minimal ladle additions are made after vacuum degassing, for example, and that the degassing equipment is properly maintained. It should be noted, however, that unless the forge facility has its own melt shop, the condition of the supplier's vacuum degassing equipment and their practices may not be known.

For some vacuum degassed alloy steel forgings, cooling in still air on completion of forging has been found to be successful. The 2.25 % Chromium—1 % Molybdenum alloy known as F22 in the ASTM Specifications A 182/A 182M Forged or Rolled Alloy Steel Pipe Flanges, Forged Fitting and Valves and Parts for High Temperature Service, and A 336/A336M Alloy Steel Forgings for Pressure and High Temperature Parts, is a good example. If cooled slowly, or annealed, this material tends to have poor machinability, being described as "gummy," but if cooled after forging in still air the machining response is very much improved. A common alloy steel, SAE 4130 is also amenable to air-cooling after forging.

For steels of higher hardenability, such as those of the nickel-chromium-molybdenum type, simple air cooling after forging is generally unsatisfactory, for several reasons:

1. Depending on the shape of the forging, especially when section sizes vary widely, the transformation products may vary considerably from one part of the forging to another. At the least, this may only adversely affect machining.
2. Depending on the forging section size, composition, and the delay before further processing, it is possible that cracking may occur during heating for subsequent quality heat treatment.
3. Depending on the section size, vacuum degassing efficiency, and particularly composition, the risk of flake damage.

As previously mentioned, before the advent of vacuum degassing, post forge flake prevention cycles were essential for essentially all ferritic steel forgings, both carbon and alloy. These were long in terms of furnace time, and usually included a normalizing stage for grain refinement. For vacuum degassed steels, the carbon and many of the low alloy grades do not require flake prevention cycles and, as was mentioned for Grade F22, may have acceptable machinability without the need for a post forge heat treatment cycle. For the higher hardenability alloy steels, a post forge heat treatment cycle is desirable to improve machinability through tempering of the transformation products, and to offset flake damage. Frequently, a subcritical annealing cycle typically at 1250°F (675°C) is adequate for this purpose.

Of particular note, precipitation hardening copper bearing low alloy steels included in Specifications A 707/A 707M, Forged Carbon and Alloy Steel Flanges for Low Temperature Service as Grade L5, and A 859/A 859M, Age Hardening Alloy Steel Forgings for Pressure Vessel Components as Grades

A and B, have been found to be particularly prone to flake damage, even when the heats were degassed under high vacuum conditions. For these materials a flake prevention cycle after forging is essential, but the subcritical anneal approach has been found to be acceptable.

Several different approaches have been used to deal with post forge cooling. Some of these rely on retarding the cooling rate after forging. This has been done by piling forgings in a heap and covering them with a refractory lined hood to cool slowly over a number of days. Sometimes an auxiliary burner is provided in the hood to further slow the cooling process. In other cases, forgings are buried in an insulating medium such as granulated blast furnace slag, and again left to cool slowly over several days. Although such systems can and do work, care has to be exercised, particularly for the sensitive grades, to make certain that the operating guidelines, often developed by trial and error over a considerable time, are not violated.

A class of materials known as Micro Alloyed Steels is used for small forgings, particularly in the automotive field, and these develop the required mechanical properties during the post forge cooling period. These will be discussed further in Chapter 9 on heat treatment and also in the review of Specification A 909, Steel Forgings, Microalloy, for General Industrial Use.

Aside from guarding against hydrogen related problems, another function of post forge heat treatment is to prepare the material for subsequent machining operations by reducing hardness and, if necessary, provide a spheroidized microstructure to help both machining and later heat treatment.

In summary, the post forge stage in the manufacture of steel forgings must be carefully considered with regard to maintaining integrity and in preparation for further processing. The cost benefits in the use of steel forgings, other than those involving ASTM Specification A 909, in the as forged condition rather than after a quality heat treatment, need to be carefully weighed against the risks. Particularly in the larger section sizes, perhaps of the order of 6 in. (150 mm) or greater, the as forged structure may be quite coarse depending on the forging finishing temperature. While tensile strength may not be adversely affected, ductility and toughness may have suffered, so that anticipated "typical" properties may be absent.

8

Machining

FOR MOST APPLICATIONS, EVEN CLOSED DIE forgings will require some machining. Machining of open die forgings is expected to be more extensive, and can involve almost all of the operations to be found in a modern machine shop. Machining, apart from bringing the forging to the required dimensions, also removes surface scale and imperfections as well as the decarburized skin. Depending on the application, some closed die forgings may be acceptable for use simply after scale removal, as for example, by shot blasting. The decarburized surface, however, remains in this case, and will offer reduced fatigue strength. Examples of the use of die-forged components with at least some as-forged surfaces include some automotive suspension parts and some piping fittings. Good examples of combined as-forged and machined surfaces are the closed die forged or continuous grain flow crankshafts used in automotive, locomotive, marine, and aero applications. In these applications, the areas that see low operating stresses in service—such as the webs—are left in the descaled, as forged condition, while the highly stressed main bearing and crankpin journals are machined to close tolerances and high surface finishes. In this example, variations in section size, and therefore mass in the as forged locations, caused by forging tolerances, are countered by dynamic balancing of the finished crankshaft.

Depending on the manufacturing philosophy of the forging producer, the amount of excess stock on an open die forging will depend to some extent on the amount of time and the number of tooling changes taken at the press to make the forging, and the cost and efficiency of the machine shop in roughing off most of the excess stock. Another related factor in this is how much of the work in making a hollow product, like a pressure vessel shell, is done at the press in making a hollow forging, as opposed to making a solid forging and machining the bore. Undoubtedly, in terms of the hot forging work done, the hollow forging far exceeds the solid forging that is subsequently bored. This is because of the sheer magnitude and number of the forging operations required to make a large hollow forging. As previously explained, these include:

Operation	Forging Work
Prepare ingot for upset and sadden	About 1.5:1
Upset	50 %
Hot Trepan	Remove ingot core
Expand the bore	Trepan bore size versus Mandrel diameter
Draw length to size and reduce wall thickness	(Wall thickness reduced by 50 % is often a requirement)

For the solid forging, the work could include ingot saddening, upsetting, and drawing back to the required outside diameter. The need to upset forge would depend on the required ingot diameter relative to the required forging diameter to assure a forging ratio of at least 3:1. Another factor that has to be taken into account is that the weight of the solid forging must fall within the capabilities of both the melt and forge shops, as well as the machine shop.

After completion of forging, and usually before the post forge cooling and heat treatment cycles are begun, it is usual practice to remove the forging discard material. For a hollow forging, and often when an upsetting operation is to be used, some of the ingot discard is taken during ingot preparation. For example, the bottom discard including the ingot plug or stool if used could be removed by flame cutting before upsetting. Similarly the hot top, if not required as a tong hold, as is the case for hollow forging, could be removed before upsetting and hot trepanning. In the case of a solid forging, the tong hold and any remaining bottom discard would be removed by flame cutting very soon after completion of forging, so that the remaining heat in the piece is used to advantage.

For both solid and hollow open die forgings, the first operation is to lay out the forging to locate centering marks and ensure that the required major dimensions can be met. For large hollow forgings it is often necessary to fit a spider into the bore to provide centers for turning the outside diameter (OD). Initial turning operations involve the use of high horsepower lathes and carbide tooling without coolant to hog off excess stock, not to mention heavy surface scale. Large circular carbide tipped saws and bandsaws as shown in Fig. 8.1 are frequently used to cut forgings to length or to separate multiple forgings.

Boring forging is a highly specialized procedure for many industrial and defense related applications. Frequently, this is done on very long pieces of the order of 40 ft (12 m) or more in length, and involves the use of specialized boring lathes. Boring can be done in two ways, by removing the material entirely as chips or swarf, an operation sometimes known as spade drilling, or by trepanning a core from the piece, a typical cutter being shown in Fig. 2.6, and then opening the bore to the required size by additional boring cuts using special hognose boring heads, so called because of their shape. These heads are often made from hardwoods mounted on a steel mandrel and are designed to support and align the cutters. In both systems again carbide tooling heads are used. The choice of system is one of economics. For blind bores trepanning is possible, but requires that the end of the core be notched by the use of special trepanning head cutters, and this limits the bore sizes that can be made in this way. For through bores in long pieces trepanning is efficient and can be used over a wide range in

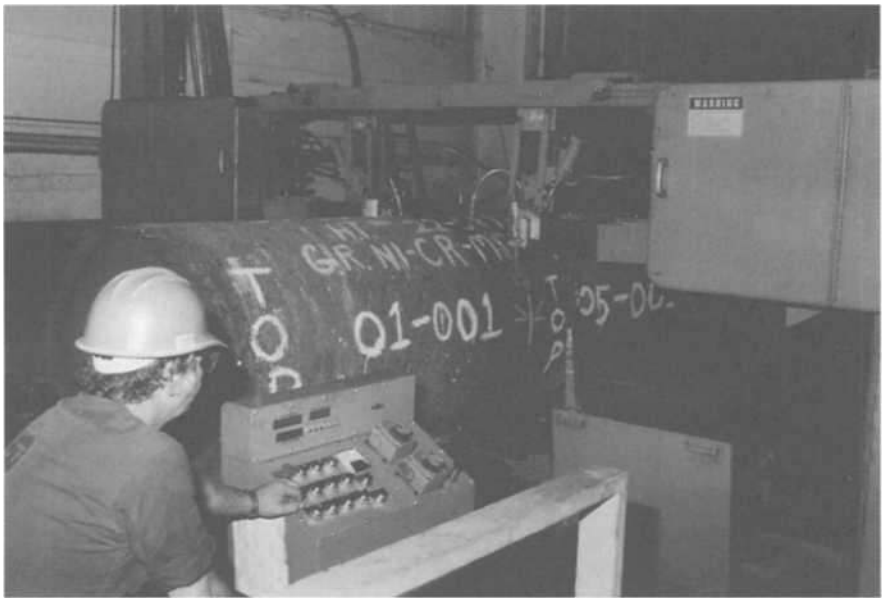

Fig. 8.1—Large bandsaw used during rough machining operations on forgings.

bore sizes from about 5 in. (125 mm) to over 30 in. (750 mm). Depending on the type of steel used there can be a significant economic value to the core bar removed during machining beyond its worth as heavy scrap.

Bore finishing operations intended to impart final dimensions and surface finishes are often done using rotary hones; however, these operations would be delayed until after heat treatment. Straightness in long bored forgings especially after heat treatment can be a problem, and bending under a straightening press or localized mechanical peening can be done to correct unacceptable bowing.

Machining of large disk shaped forgings is usually done in vertical boring mills, and specialized machines of this type are used also for surface contouring and short boring operations that might be associated with making pump blocks, or integral nozzles in forged vessel shells. This type of combined component reached astonishing heights with the production of forged nuclear reactor pressure vessel heads and sections with integrally forged nozzle belts, as shown in Fig. 2.2, that were welded to forged shells by circumferential seams only. This eliminated weld joints that are difficult to examine under in-service inspection rules. Rules of this description have engendered other forging designs ideally suited to open die forgings. Examples, again associated with nuclear power plants, are the containment penetrations, Fig. 2.10, for main steam, water, and instrument lines. Where these pass through the concrete shielding walls, the process pipes are kept away from the concrete by the use of guard pipes that are concentric with the process pipe, providing an annular space for insulation. This guard pipe is attached to the process pipe, and to avoid a fabrication with many welds, and to assure that any circumferential welds are located clear of the concrete of the containment system, forged pipe sections, up to 40 ft (12 m) in length, were produced with an integral guard pipe head at one end. Some of these were produced as solid forgings subsequently bored and heat treated, and some were produced from back extruded steel pipe forgings with the integral guard pipe head section spun from excess stock left at one end. Consultation with the forging manufacturers is essential for this type of innovative design procedure to work.

Although lathes, milling machines and vertical boring mills are commonly used in machining forgings, the larger pieces often require custom designed machines to accommodate their size and particular machining needs. Figure 8.2 shows a marine steam turbine rotor forging in a large lathe, and demonstrates the substantial supports that are necessary in operations such as gashing the rotor body between adjacent wheels.

Grinding

Surface grinding can play an important part in the finish machining of forgings, particularly when dealing with locations obtained after surface hardening by carburizing, nitriding, or flame or induction hardening. In the hardened condition such finishes are extremely difficult or impossible to machine with conventional tooling, and grinding is a cost-effective method of achieving dimensional requirements and high degrees of surface finish. The drawback is the real risk of locally overheating the surface and inducing surface cracks. These tend to be oriented at right angles to the direction of travel of the grinding head, and often appear as a circumferential or longitudinal track. The cracks are typically short, straight, and with forked ends. They frequently will not be visible to the eye, requiring magnetic particle or liquid penetrant examination to reveal them. The cracking mechanism begins with local heating during contact with the grinding wheel producing skin temperatures high enough to locally austenitize the material—temperatures of the order of at least 1500°F (815°C)—followed by immediate quenching by heat conduction to the underlying base material, aided by the presence of the grinding coolant. The root causes of this problem are inadequate dressing of the grinding wheel such that it does not cut the surface properly, or accidentally using excessive feed, but both of these are re-

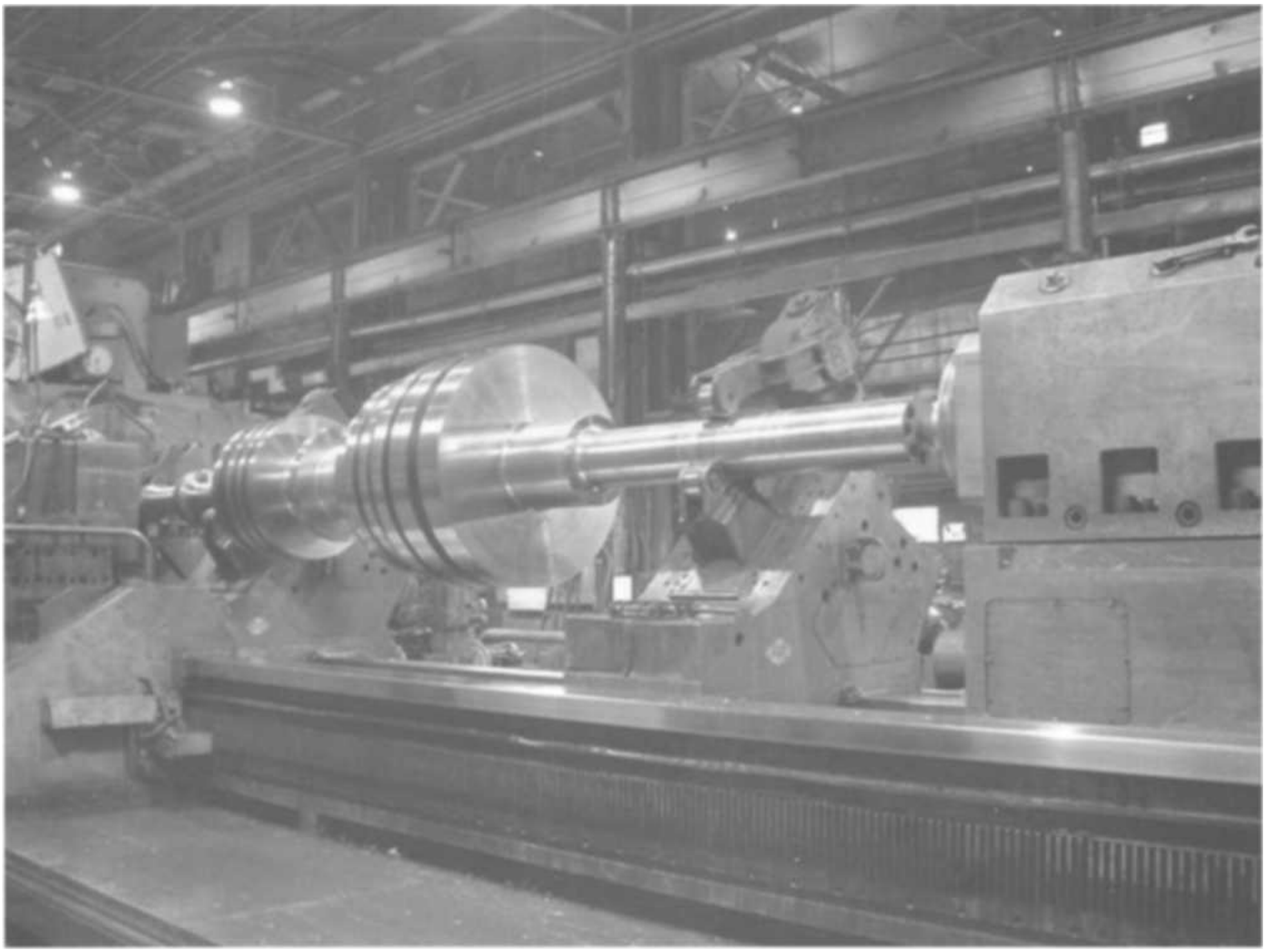

Fig. 8.2—A large steam turbine rotor forging in a lathe used for turning the rotor journals and gashing the blade wheels. Some idea of size can be gained from the size of the mechanical test core holes in the end of the shaft portion. The test cores themselves are about 1 inch (25 mm) in diameter and the holes left by the trepanning tool are over 1¾ in. (45 mm) in diameter. Lathes of this type have high kWh power ratings. (Courtesy of Ellwood National Forge Company)

lated in that excessive heat is generated at the working surface, despite the apparent copious supply of coolant. White (untempered) martensite forms in the heated and quenched area and with it localized cracking. This type of defect is unacceptable for most applications, and is especially deadly for any that involve cyclical loading. Since the component is at finished size when these defects form, recovery is frequently impossible. This type of cracking is similar to the heat checking that is associated with bearing seizures and is shown in Fig. 11.3.

Fear of grinding cracks should not make the manufacturer shun the use of surface grinding; rather, the problem should be recognized and work procedures written and followed to assure that they are most unlikely to occur. In passing, it should be noted that the use of poor quality grinding media, and particularly the use of substandard diamonds for dressing the grinding wheels, should be avoided. This is mentioned because those responsible for obtaining these materials may not be aware of their importance.

Mention is made here of highly specialized grinding systems known as Creep, or Creep Feed Grinding, whereby very heavy grinding cuts can be made on hardened surfaces without causing cracking or softening. Part of this technology involves the use of grinding wheels that permit a high volume flow of coolant *within the wheel itself*, as opposed to only flooding the wheel surface and the surrounding work piece. The longitudinal flute forms in the corrugating rolls used to make corrugated paper board can be produced by this process in one or two grinding passes.

Because very little stock needs to be removed from a nitrided surface, quite often this surface hardening operation is done after grinding, and only very light surface finishing work is done afterwards to remove the white layer and shine the surface. However, even this operation must be approached with care. A situation was encountered during the failure analysis of a nitrided crankshaft in SAE 4130 material. The multiple origin fatigue failure was traced to grinding cracks in a nitrided main bearing thrust face located on the web just above the main bearing fillet. It was later found that the thrust face had been ground using a dulled grinding media, and that the resulting fine grinding cracks were not detected during final magnetic particle examination, possibly because of their radial orientation.

Before leaving the subject of machining some mention should be made of *machinability*. This is a complex subject in its own right, and is only mentioned here in terms of some of the effects that the forging material itself lends to the subject. It is well known that some nonmetallic inclusions assist in improving machinability by acting as chip breakers, and some globular inclusions produced by inclusion shape control are claimed to assist both as chip breakers and in providing some lubricity to the cutting tool. The use of manganese sulfide as a means to improve machinability is common, particularly for some automatic lathe operations. Free-machining steels, such as the 11xx series in Specification A 29/A 29M, "Steel Bars, Carbon and Alloy, Hot Wrought and Cold Finished, General Requirements for," are deliberately resulfurized (0.08–0.13 % S for example) during steel making, and the steels for some bar materials are leaded (0.15–0.35 % Pb) for this purpose. These materials generally have inferior mechanical properties to the non free-machining grades, and also for the leaded steels lead fume could pose a serious health risk for fabrication by welding. For the high sulfur or selenium steels inclusion shape control by means of calcium or mischmetals can help in maintaining ductility, the improvement being most marked when the inclusions are small and widely distributed [1]. It should be remembered always that the advantages of free-machining materials are left in the chip box or on the machine shop floor.

References

[1] Shiiki, K., Yamada, N., Kano, T., and Tsugui, K., "Development of Shape-Controlled Sulfide-Free Machining Steel for Application in Automobile Parts," SAE paper 2004-01-1526, 2004 SAE World Congress.

9

Heat Treatment

THE PUBLISHED ISOTHERMAL TRANSFORMATION and continuous cooling transformation diagrams for the standard steel grades are extremely useful in understanding the capabilities of these materials, and should be considered in conjunction with the published hardenability data, such as that included in ASTM Specification A 914/A 914M, Steel Bars Subject to Restricted End-Quench Hardenability Requirements, when setting up a heat treatment cycle. The emphasis in this chapter is on techniques and equipment.

Annealing

Unless otherwise prefaced, the term *Annealing* applies to the slow furnace cooling of ferritic steels from the austenitic temperature range to below the lower critical temperature Ar_1. Although this is sometimes referred to as *Full Annealing*, if the forging specification or order calls for annealing, then this heat treatment is required. It should be noted that the benefits of annealing are only obtained if the treatment is applied after the forging has been allowed to cool and transform after completion of the forging work. Simply slow cooling after finishing forging will offer some protection from defects such as flake, but will do nothing to refine the microstructure or even out structure differences throughout the forging. Annealing applied after the forging has transformed will permit structure refinement, significantly reduce residual stresses, and improve machinability.

As an extension of the post forge heat treatment, *Spheroidizing Anneals* are used, as the name suggests, to spheroidize the carbides to markedly improve machinability, particularly for the high carbon grades such as those used for ball and roller bearing applications. These treatments tend to be long and are, therefore, expensive in terms of furnace time. The spheroidizing effect is achieved by holding the material just under the lower critical temperature for the grade. Sometimes cycling the part just above and then just below this temperature assists in this goal and reduces the holding time. The degree of spheroidization is measured by microstructure evaluation. Spheroidizing also assists in subsequent heat treatment by enabling more complete carbide solution when the steel is austenitized.

The third annealing variant is *Subcritical Annealing*. This was referred to under post forge handling, and involves heating the forging to a temperature below the lower critical temperature, followed by air or furnace cooling. This is similar to a tempering or stress relieving operation, but the hold time at temperature may be extended, particularly if hydrogen diffusion is sought.

For the austenitic materials, a solution treatment is usually called for and this is frequently referred to as a *Solution Annealing* treatment, and is followed by water quenching or some equivalent rapid cooling procedure. A requirement for most austenitic steel forging specifications, this cycle is sometimes permitted in the form of quenching or rapid cooling from the forge finishing temperature. To be effective this procedure sometimes referred to as In Process Annealing obviously needs the quench or cooling facilities to be close to the press. For large forgings this approach is not practical.

Micro-Alloyed Forgings

In contrast to many rolled bar, plate, strip, and tubular ferritic steel products that are frequently used in the as hot worked condition, most forgings are expected to be heat treated before use. Exceptions to this are the micro alloyed forging materials where the intent is that control of the cooling rate after forging is sufficient to develop the required mechanical properties. This demands close control on the forging parameters in terms of forging temperature, hot working, and finishing temperature. The cost of a heat treatment cycle is, therefore, avoided. It will be apparent that for this to work on a consistent and reliable basis that a repetitive programmed operation is required, as would be the case for the large-scale production of essentially identical closed die forgings. There are significant size limitations for this type of forging. The micro-alloyed forging steels are mainly carbon manganese steels with vanadium, niobium (columbium), molybdenum, and or titanium in small amounts, each less than 0.30 %. Minimum yield strengths up to 100 ksi (690 MPa) are possible in these steels. Microstructure requirements can be used as an additional quality assurance tool. Many forgings of this type are used in automotive applications, and ASTM Specification A 909, "Steel Forgings, Microalloy for General Industrial Use," can be used for forging procurement purposes. A forging procedure is advisable when ordering this type of forging.

Carbon and Alloy Steel Forgings

Except for very small forgings weighing a few pounds or kilograms, typical perhaps of the micro-alloyed type, for the most part the use of nonheat treated forgings can have serious drawbacks, not the least of which is lack of uniformity. This risk increases with the forging size. Brittle fracture in service has been associated with forgings that had not received a full reaustenitizing heat treatment following post forge transformation. The forging finishing temperature influences the microstructure that will form on cooling, and in a large forging the temperature at which hot working ends can vary significantly throughout the piece. It follows then that even when forgings are not required to be heat treated that serious thought should be given to applying heat treatment none the less, since this can accomplish grain refinement and aid in equalizing the effects of variations in the forging finishing temperature.

Normalizing is the simplest of the suitable heat treatment procedures that can be used for this purpose and consists of heating the material into the austenitic range, holding or soaking at temperature long enough to permit the full cross section to come up to temperature, followed by cooling in still air to ambient temperature. The effect is to refine markedly the microstructure, and this probably accounts for the name of the term. The temperature used for this operation depends largely on the carbon content of the steel but often could be 1650°F (900°C). In situations where the material is austenitized twice as in a *Double Normalize and Temper* cycle, or preparatory to a *Quench and Temper* cycle, the temperature for the initial normalizing is sometimes raised to 1700/1750°F (925/955°C) to help take carbides into solution. The choice of austenitizing temperature is a compromise between efficiently taking carbides into solution and avoiding grain growth. Time at temperature is often measured after the furnace thermocouples come up to temperature, and a frequently used yardstick for this is to allow 1 h/1 in. (25 mm) of maximum section thickness. If thermocouples that actually contact the piece are used, then this time span can be reduced, but not below 30 min/in. (25 mm) of maximum section thickness. Although by definition cooling for a normalizing cycle is done in still air, fans are often used to speed the cooling, particularly if the forging exhibits very marked section changes, as in the case of a large diameter roll with integral arms or trunnions when fans might be directed onto the roll body section.

Tempering, that is heating the forging to a temperature lower than the lower critical temperature, is often used after normalizing, particularly for the higher carbon grades. This tends to reduce the hardness attained after normalizing and reduces any residual transformation stresses. However, for plain low to medium carbon steels (carbon up to about 0.50 %), especially in section sizes over about 4 in. (100 mm), tempering will show little noticeable effect on the tensile properties, unless the normalizing cycle has given rise to a bainitic microstructure.

Rapid cooling from the austenitizing temperature is used to develop bainitic or martensitic microstructures, and this type of heat treatment is used to develop the optimum strength and toughness properties in both carbon and low alloy steels. The cycle consists of an austenitizing stage, followed promptly by rapid cooling, usually by liquid quenching, although in a few cases forced air or forced air with water misting is used. Following this rapid transformation, the forging is given a subcritical tempering cycle. This heat treatment is usually referred to simply as a *Quench and Temper* cycle. As in the case of normalizing, the choice of austenitizing temperature for the quench and temper depends on the steel composition, or more particularly on the carbon content, but for the common low alloy steels such as Grades 4140 or 4340 of Specification ASTM A 29/A 29M, a common temperature would be 1550°F (845°C), and if a preliminary normalizing cycle were to be used this would be done at 1650°F (900°C).

Although not always necessary, particularly when a well-developed forging procedure enables a low finishing temperature to be achieved on a consistent basis, the preliminary normalizing cycle is a most useful preparatory step to austenitizing for quenching. This is particularly true for a bored or hollow cylindrical forging, when the initial normalize has been found to significantly reduce the risk of quench cracking. This becomes particularly important with higher alloy grades with carbon contents over 0.35 %.

Variations exist on the theme of these basic heat treatment cycles used in order to extract (sometimes coax is a better word) the required properties from a particular material in a particular forged shape and size. Double quenching with or without a preliminary normalize is an example of one such option.

While tempering of forgings after normalizing is sometimes optional, in practically all cases it is mandatory after quenching. After effective quenching, particularly when transformation to martensite has been achieved, the material is typically hard and brittle and it is necessary to temper the steel to improve ductility and toughness at the expense of some hardness or tensile strength. Depending on the material used this trade off need not be too severe. Generally speaking, for the low alloy steels tempered martensite gives the best combination of yield strength, tensile strength, elongation, reduction of area, and impact toughness. Lower bainitic structures are not quite as good, but are better than the properties obtained from an upper bainitic structure. These structural choices, of course, are achieved during the quenching operation. For most steels, as the tempering temperature is raised the tensile strength and hardness decrease and the ductility and toughness increase. The degree of improvement in toughness and ductility, however, is also tied to steel cleanliness. For a few steels, (for example Grade 84 of Specification A 579/A 579M) secondary hardening effects occur as the tempering temperature is raised, and this effect can be used to advantage, because toughness is not necessarily degraded.

Age Hardening: Although usually associated with several nonferrous materials such as aluminum alloys, age hardening or precipitation hardening is applicable to certain stainless steels such as the Maraging group, as included as Grades 71 though 75 in Specification A 579/A 579M, Superstrength Alloy Steel Forgings, and Grades 61 through 64 that include the group known generally as 17-4PH and 15-5PH stainless steels. The heat treatments for these alloys involve solution treatment, after which most of the machining is completed before the hardness is increased by intermetallic precipitation during the aging stage. The Maraging steels are low carbon, nickel-cobalt-molybdenum containing alloys with titanium and aluminum and their heat treatment is discussed in the Metals Handbook [1].

The nickel-chromium-copper age hardening alloys of the 17-4PH and 15-5PH types also require solution treatment prior to the age hardening cycle, and this is discussed also in the Metals Handbook [1]. Following the heat treatment procedures for the age hardenable stainless steels is essential.

Heat Treatment Equipment

Successful heat treatment hinges not only on quality steel and properly prepared forgings but also on first class equipment including furnaces, rigging, and cooling facilities, as well as the necessary expertise.

Furnaces

Precise temperature control in terms of rate of temperature rise, set temperature, and uniformity within the furnace working zones are critical for effective heat treatment. ASTM Specification A 991/A 991M, Test Method for Conducting Temperature Uniformity Surveys of Furnaces Used to Heat Treat Steel Products, gives the basis for establishing minimum furnace requirements and is embodied in Specification A 788, Steel Forgings, General Requirements.

Furnaces for the heat treatment of the larger forgings are usually of the batch type, while continuous furnaces are most often used for smaller parts especially when larger quantities are involved.

Batch Furnaces

Batch heat treatment furnaces fall into two main types, vertical and horizontal. In the vertical type, the parts can be hung in the furnace, or in the case of very heavy forgings may be supported on a structure (usually temporary) at the bottom of the furnace. In the horizontal type the forgings are supported on bolsters resting on the furnace car bottom. The furnace car generally runs on rails to facilitate loading and unloading. Except for relatively short units up to about 10 ft (3 m) in length, industrial horizontal and vertical batch furnaces are divided into individually controlled heating zones to facilitate temperature control. The furnaces are typically natural gas fired, although provision may be made for dual fuels, using oil as an alternative. Experience with natural gas supply restrictions, especially in the colder areas, and cost has made this type of furnace operation prudent in the past. However, although oil is an acceptable fuel for forge heating purposes, gas firing is much preferred for heat treatment operations because of superior temperature control and reduced maintenance. Soft fiber type refractories are now preferred for furnace lining, permitting rapid cool down of the furnace at the end of the cycle.

Horizontal Furnaces

The furnaces are designed to work under a light positive pressure to enhance uniformity, and it is most important that attention is paid to sealing round the furnace car and the door. As with any furnace, the load must be properly placed within the working zone, and provision is made for adequate furnace gas circulation around the workpieces. One sometimes sees pictures of components piled high on a furnace car, and the inference is that either the heating was uneven or an excessively long time was allowed for the load to come up to temperature.

Support rigging is needed in horizontal car bottom furnaces, to hold the forgings clear of the car floor and permit crosswise gas circulation. As in the case of the horizontal forge heating furnaces, firing is achieved by means of a row of natural gas burners firing across the car below the level of the bolsters, and on the opposite furnace wall a second burner row firing over the charge. In this way flame impingement is avoided and circulation promoted. During austenitizing cycles there is a tendency for scale to build up on the furnace car, and this should be removed before it impedes furnace gas circulation. The furnace car bolsters also perform another duty in supporting the load and minimizing distortion risks, so that the span between bolsters should be considered with respect to the forging dimensions.

Furnace thermocouples are normally inserted through ports in the furnace roof, and again the use of a control or zone thermocouple and a check couple is common for each furnace zone. The vertical position of the thermocouples should be adjusted to lie just above the load. Also for more critical work, thermocouples can be attached to the workpieces, or held in contact with the load.

Recuperative burners are available to economize on fuel costs.

Small muffle furnaces of the type used in tool heat treatment and laboratories are simply loaded and unloaded through the furnace door. This type of furnace is frequently heated by an electrical resistance wire wound around the furnace lining, or by exposed glowbar strips heaters, although gas firing is also used on occasion. For some applications, particularly for annealing and post forge heating cycles, the forgings are placed on a refractory floor and an insulated hood fitted with burners for heating is placed over the charge.

Vertical Furnaces

Vertical heat treatment furnaces are invaluable for the heat treatment of long products, particularly if they are bored, and for critical components such as turbine and generator rotor forgings. The forgings are usually hung in the furnace, often from the furnace door, permitting even heating, and freedom from sagging that might occur during the soak stage of the austenitizing cycle if the part were to be laid horizontally over bolsters on a horizontal furnace car. Like the horizontal furnaces the vertical furnace working space is divided into zones generally of the order of 10 ft (3 m) in length. Typically, the burners are disposed in circumferential belts and are oriented to fire tangentially into the furnace space to assist in circulation and avoid flame impingement. The furnace flue is typically situated at the bottom of the furnace, and like the horizontal type heating is done by natural gas, and the furnace operates under a slight positive pressure. Vertical furnaces are generally easier to seal than the horizontal type, not having the long leakage path round the furnace car.

Although vertical furnaces take up less floor space than horizontal type, sufficient headroom must be allowed to permit crane loading and unloading. For a furnace that can accommodate perhaps a 40-ft (12-m) long shaft, it is apparent that a similar amount of overhead clearance will be required to get the forging in and out of the furnace. For this reason, it is common for vertical furnaces to be installed at least partially in pits. However, the level of the site ground water table can present problems in facilitating this. Some innovative designs aimed at overcoming the headroom problem have used a vertically hinged furnace shell.

Although in general forgings are suspended from the doors in vertical furnaces, it occasionally happens that this is not possible due to the weight of the piece, or because of a need to use cold rigging. In this circumstance the use of a stool in the furnace would enable the part to be lowered into the furnace before starting the cycle, and supported in the working zone without impeding gas circulation. The stool would be removed at the end of the cycle.

At least a part of the rigging used to suspend the piece in the furnace must withstand the full austenitizing temperature and the soak time being used during the cycle. For many applications common materials such as SAE 4130 will suffice, rather than a heat resisting nickel base alloy, and give repeated service before stretching under load and scaling significantly enough to thin the cross section.

Temperature control is maintained by permanent zone thermocouples that penetrate the vertical furnace wall. Contact thermocouples are often used to record the forging temperature as well. Readings from this source can be used to indicate when the forging has reached the required temperature.

Continuous Furnaces

For the repetitive programmed heat treatment of essentially the same type of component, continuous furnaces may be used. These use a moving heat resistant belt or hearth and accept the component cold, heat it at a controlled rate to the required temperature, and after the required soak time the part exits the furnace for quenching or other controlled cooling operation. The furnaces are usually horizontal but may be in-line or rotary, and heating may be done by oil, gas, or electrical methods. Although generally used for repetitive smaller products such as automotive parts, specialized heat treatment lines have been set up for some fairly large products such as oil field Kelly Bars, and for the military, tank cannon barrels. A disadvantage of such installations is that they require the material to have hardenability characteristics within close limits, and may be unable to deal with a heat of steel that falls just outside the expected norm, a situation that conventional batch heat treatment could handle with little or no difficulty.

Continuous heat treatment lines often include quench facilities, and these can be expected to be dedicated to the materials commonly put through the facility. They are also a potential Achilles Heel for product specifications clauses that permit relaxed mechanical testing requirements for heat treatment in continuous furnace lines.

Induction Heating

Increasingly, induction heating is being employed for continued production of the same part. As mentioned in connection with induction heating for forging, temperature control is vital and can only be achieved with a rigidly defined process. While gating methods can be used to eject components that are under or over the preset temperature limits, great care must be taken to assure that if the rejected parts are to be reheated that they have fully cooled to ambient temperature before starting through the line again. Closely matched material in terms of hardenability is required as is the case for continuous furnace lines. The advantages lie in speed, low energy consumption, and space saving. Induction heating is unlikely to be used for the general quality heat treatment of open die steel forgings.

Controlled Atmosphere/Vacuum Furnaces

In situations where decarburization or scaling cannot be tolerated, as for example in heat treating tools where a hardened cutting edge must be maintained, or for components such as springs that are heat treated in the finished state, and where decarburization would seriously reduce fatigue strength, heating to the austenitizing temperature under vacuum or in a neutral or reducing atmosphere can be used. Controlled atmosphere furnaces are often heated by natural gas or radiant tubes and are sometimes of the continuous type, but vacuum furnaces are of the batch type, are electrically heated, and often include facilities for controlled cooling using an inert gas.

The use of electrically heated furnaces for large forgings is uncommon, possibly because of peak and off peak electricity tariffs, but some examples are known where electric vertical furnaces have been used for subcritical tempering applications. Some form of air circulation is required for such furnaces.

Cooling/Quench Facilities

If precise control is required in furnace operation, equally great care must be taken in the provision and operation of the cooling facilities, particularly if this involves liquid quenching.

As mentioned earlier normalizing is, by definition, cooling in still air from the austenitizing temperature. An important part of this is unobstructed cooling with free air circulation, meaning that the part should not simply be dumped on the floor, but be placed on rails or bolsters. This is particularly the case for air hardening steels. For large parts carefully aimed fans may be necessary to direct cooler air over the work. For some specialized components such as chromium-molybdenum-vanadium high temperature turbine rotor forgings, air cooling is done while the rotor, suspended vertically, is rotated in a cooling tower with ducted forced air directed tangentially over the rotor surface. This enhanced air cooling is used to coax improved toughness properties from the air-cooled forgings.

Leaving forgings to cool in a pile on the furnace car is not recommended for uniform normalizing, since heat from the car refractories and bolsters will contribute to uneven cooling.

Liquid Quenching

Three liquid media are used in liquid quenching. These are water, oil, and water based emulsions generally of water and a polymer. The quenching medium is contained in a tank fitted with some form of agitation device and provision for both recirculation and make-up. The tanks generally follow the format of the furnaces, horizontal tanks with horizontal furnaces, and vertical tanks with vertical furnaces. Horizontal and vertical spray quenching equipment needs an adjacent storage tank as a reservoir. Adequate circulation of the quenching medium is an essential feature of any quench facility and should be a part of the original design.

Water Quenching

Water is probably the most commonly used, and with its high heat capacity, the most efficient quench medium. It should be remembered, however, that above about 120°F (50°C) the efficiency of water as a quenching medium drops off because of the onset of steam formation, since steam bubbles on the quenched surface act as insulators. It is this tendency, or in other words, the suppression of steam blanketing that requires the use of efficient quench tank agitation, so that cooler water is continuously brought into contact with the hot surfaces of the workpiece. This is particularly true of quenching hollow items where it is often difficult to get a free exchange of water through the bore. The real danger here is that steam blanketing will occur in the bore and lead to quench cracking. This is one of the situations where preliminary normalizing of high hardenability forgings is helpful in avoiding quench cracking.

Good quench tank agitation can be achieved with mechanical impellors or by the use of high volume pumps to circulate the water in the tank, or both. The use of compressed air for this purpose, although visually impressive, is not recommended, since it reduces the heat capacity of the tank. If the part is suspended in the quench tank by means of the crane that was used to remove it from the furnace, then the crane can be used to cycle the forging up and down in a vertical tank, or back and forth in a horizontal tank. This is particularly helpful during the important initial stages of the quench, especially for hollow components. Use of piping nozzles can be very helpful in dealing with bored products by directing a positive stream of cold water into the bore. A technique for prequenching the bore of long forgings, such as large cannon barrels, for perhaps a minute or two prior to immersing the whole forging in the tank has been used in some shops as a means of preventing bore quench cracking, but it should not be necessary to go to such lengths. Ensuring that the quench water is cold at the outset is a sound recipe for successful heat treatment; however, this is not always as easy as it sounds. Often the source of the water is the city's water supply, and depending on the source this can get quite warm during the summer months. This could mean a make up water temperature of over 80°F (25°C) for a tank whose starting temperature was already high. In one such situation, a refrigeration unit had to be installed to bring the initial water temperature down to an acceptable number. The quench tank water temperature should never exceed 75°F (25°C) before quenching starts and should never exceed 120°F (50°C) at any time during the quench. In some locations, quench water is available from private wells rather than municipal supplies, and heat exchangers are not required. In one such instance, the well water maintained a more or less even temperature of about 55°F (13°C) year round, greatly assisting the quenching efficiency.

Monitoring of the water temperature during quenching is an important quality assurance tool, since this information can provide guidance on the performance of the operation and when assessing the results of mechanical testing and nondestructive examinations. The water temperature should tend to rise fairly quickly in the first few minutes of the quench, then the rate of rise should decrease, level out, and then gradually fall. When lifted out of the tank near the end of the quench, the surface temperature of the part should be measured—infrared thermometers are very useful for this—and then measured again after a short time period, 5 min is commonly used. If the surface temperature rises by more than 100°F (55°C), the part should be immersed for a further time period until a lesser temperature bleed back is observed. Such data are most helpful if the situation should arise that the anticipated properties were not obtained. Unfortunately, the collecting of such data is sometimes axed in the interests of reducing costs.

It is important for the forging to be quenched properly to avoid the formation of undesirable transformation products, particularly in the heavier sections. More than one brittle failure in high strength nickel-chromium-molybdenum steel, such as the example shown in Fig. 9.1, has been traced to over hasty cessation of the quench stage of the heat treatment cycle.

It goes without saying that the time taken from the opening of the furnace doors until the piece is immersed in the quenchant should be as short as possible to avoid slack quenching situations. For this reason the cranes used in the heat treatment shop should be capable of rapid lifting and movement, and in turn the shop personnel should be well trained and rehearsed in the movements that have to be made. This is necessary in terms of safety as well as efficiency, and applies to any heat treatment operation.

Although the medium carbon steels such as Grade 1045 of ASTM A 29/A 29M can be water quenched with a reasonable degree of safety, in the case of the alloy steels such as the chromium-molybdenum 4100 series and the nickel-chromium-molybdenum 4300 series the heat carbon content should not exceed 0.35 % if water quenching is to be used.

Brine is sometimes used to increase quenching efficiency. Like oil and polymer emulsion quenching media, this requires the use of a heat exchanger, and unlike these other quench media could cause serious corrosion in the quenching system, including the pumps and piping.

For the alloy steels in particular, retained austenite is a factor to be remembered since more than about 0.5 % in the microstructure is likely to adversely affect the mechanical properties. In most cases, retained austenite is transformed during tempering, and double tempering is especially useful for this purpose. Holding at cryogenic temperatures, for example, by the use of liquid nitrogen is helpful for the transformation of retained austenite in the more highly alloyed

Fig. 9.1—Brittle failure during hydrostatic testing of a large thick-walled alloy steel pressure vessel for a cold isostatic press. Investigation showed that the principal cause was poor heat treatment that left the forging with a high ductile to brittle transition temperature.

steels, and is necessary for some of the superalloys such as Grade 82 in Specification A 579/A 579M before tempering. It should be noted that martensite formed during cryogenic temperatures is untempered, and some form of tempering afterwards is desirable if not mandatory.

Oil Quenching

Oil quenching is considerably less drastic than water quenching and is, therefore, applicable to high hardenability steels, in particular those with carbon contents higher than 0.35 %. Many tool steels fall into this category as well as common alloy steels such as the SAE grades 4140 and 4340. The oils used today are mineral based and vary in viscosity index. The typical oil quench facility used for large forgings must have provision for heating the oil prior to the quenching operation. This is because circulation and agitation of the oil is difficult at ambient temperatures, and in association with this if quenching proceeds into cold oil, slack quenching, uneven heat extraction, and a high risk of cracking and fire are likely. Typically, the oil is heated to about 120°F (50°C) before starting the quench. A heat exchanger is necessary to cool the oil as it circulates. This is usually water-cooled and points to a maintenance area that requires careful supervision. Water leaking into the quench oil will cause excessive foaming during quenching, much as the effect of plunging a basket of French fries into hot oil. This can have the potentially disastrous effect of overflowing the tank, and heightens the fire risk. The opposite scenario of oil leaking into the cooling water system can lead to an oil film on the water-side of the heat exchanger with a drastic loss in cooling efficiency. The volume and, hence, heat capacity of the oil quench facility relative to the weight and form of the forging to be quenched must be kept in mind. A bored piece exposes a much greater hot surface area to the oil than the same part that has not been bored prior to heat treatment, albeit that the heavier solid forging brings more heat to the tank in total. Since the flash point of the oil would be expected to be about 350°F (175°C), too large a piece could start a dangerous fire, being fed by additional hot vapor from the tank as the forging is being cooled.

Oil quenching tends to produce less dimensional distortion and reduced risk of cracking than water quenching, often at the expense of lesser mechanical properties in the quenched material. As has been mentioned, however, particularly when the carbon content exceeds 0.35 % and depending on the configuration of the forging, oil or polymer quenching may have to be used. As an example, a particular forging in SAE 4340 with a heat treated section size of 6.5 in. (163 mm) was required to meet a low temperature Charpy value that while unattainable by oil quenching, was possible if water quenching was used. The material could not be changed to a lower carbon, higher nickel grade, but the shape was symmetrical with no section changes. Water quenching was successful when careful attention was paid to machining the forgings for heat treatment, including rounding all of the edges to remove sharp corners.

One technique, known as water to oil quenching, that is used when dealing with a forging that is marginally too large for a given oil quenching facility is to initially quench the part in water for a short interval, perhaps 2–3 min, and then transfer the forging, while still in the austenitic state, quickly to the oil tank. This can effectively and safely reduce the initial temperature before completing the quench in oil. The risk of carrying entrained water to the oil is negligible because of the high temperature of the forging, but of course, the oil and water tanks must be close to each other for this to work.

There are variations in the capabilities of quenching oils, and reputable suppliers are available to advise on the appropriate grade for a particular application, particularly if the need is to process essentially the same product through the heat treatment line.

A potential environmental problem associated with oil quenching occurs during the subsequent tempering cycle. This is because of smoke associated with burning off oil that has not drained from the part at the end of the quenching operation.

Polymer Quenching

Emulsions of special polymer compounds with water are important in the heat treatment of steel. The quenching effect can be controlled by the type of polymer used and its concentration in the emulsion. Generally, they are regarded as being slower than direct water quenching and faster than oil. Excess quenchant can be rinsed off the part before tempering if need be, but essentially there is little if any smoke produced during the temper cycle. This type of quenching medium has been very useful in heat treating partially machined forgings such as multibore pump blocks in high strength nickel-chromium-molybdenum-vanadium steels, where although the carbon was kept lower than 0.35 %, the forging configuration with intersecting bores during heat treatment prompted bore cracking when water quenching was used. However, when the carbon content of the steel is high, great care must be taken in quenching bored forgings in polymer emulsions. Unless very thorough flushing of the quench medium through the bore can be assured, especially during the early stages, and simply agitating by lowering and raising the part in the tank may not be enough, the emulsion tends to separate on the hot bore surface leading to spotty water quenching and inevitable cracking.

As in the case of oil quench tanks, heat exchanging equipment must be provided to cool the polymer emulsion, although here dilution by water is of importance only in terms of maintaining the required polymer concentration, and this simple operation must be done on a regular basis. It should be mentioned that there is no fire hazard with polymer emulsions.

It will be seen then that for a heat treatment facility that intends to handle a variety of material types and forging configurations the quenching options are many and varied, and compete for floor space, since necessarily they must be located near the furnaces and be readily accessible by crane. In some facilities, holding tanks are provided so that the same tank can be used for both water and polymer quenching.

Polymer Concentrations

Polymer concentration requirements vary according to the application and the maker's recommendations. Typically, they lie in the range of 15–20 %. A concentration of 17 % of a polymer from a major supplier was found to be acceptable for quenching alloy steel crankshafts with carbon contents up to 0.45 %. Some heat treatment shops use low concentration polymer emulsions at about 5 %, where the steel involved would normally be water quenched. The justification for this is not clear. Generally, as the polymer concentration increases the quench severity decreases and the quenching effect draws closer to oil.

Spray Quenching

It will be readily appreciated that when considering the heat treatment of specific components on a continuing basis the entire heat treatment facility can be designed, equipped, and operated in a highly efficient and reproducible manner. However, flexibility in dealing with other shapes and materials may be sacrificed. It is also apparent that in quenching, rapid controlled cooling and minimal distortion are desirable attributes. Spray quenching facilities have been used successfully in alloy steel plate manufacture, and these have found their way into steel forging heat treatment as well. Generally in spray quenching forgings, the goal is to keep the surface continuously wetted with cold water while, if the shape permits, rotating the part to ensure uniformity and reduce distortion. The equipment usually is designed to allow flexibility in handling forging shape, configuration, and weight, but again if sufficient numbers of a given design are to be produced, then a dedicated quenching rig can be designed. The water supply is usually a nearby water quench tank, into which the water can be recirculated. High capacity pumps are a requirement, since the forging surface must be kept flooded at all times. The water is sprayed onto the part through a system of jets, and these can be chosen according to the volume of water to be supplied and the desired pattern of the spray. The sprays would be arranged in longitudinal rows or in rings, such that there is an overlap between adjacent spray heads, and similar rows would be arranged around the piece. The forging is often set on a series of driven and idler rolls to enable it to be rotated between the spray heads. The spray heads themselves should be capable of being adjusted radially to maintain a given distance from the forging, thus enabling various shapes to be quenched evenly, as for example when quenching a roll shape with integral journals. Bored or hollow forgings can be dealt with in this type of quenching rig also by the use of a spray wand introduced into the bore after the forging has been set on the rolls. Blind-ended vessels have been successfully quenched in this type of rig.

The use of polymer emulsions in this type of equipment must be approached with caution by assuring adequate flow through the jets because of the risk of the emulsion breaking down and separating on contact with the hot surfaces.

Alternate Heat Treatments

Conventionally, heat treatment of the ferritic carbon and alloy steels takes place in two distinct temperature zones. One (usually the first and known as the austenitizing stage) is done at a temperature selected within the austenitic zone where complete transformation to austenite is sought, though not always complete solution of all of the carbides present, particularly in some tool steels. The other stage takes place at temperatures below the lower critical temperature and is known as the tempering stage, or if this is the only heat treatment, a subcritical anneal.

If instead of choosing a temperature in the austenitic range, a temperature is chosen between the upper and lower critical temperatures [2] (that is in the intercritical range), when the steel is cooled a marked grain refinement takes place. Although the tensile and yield strengths are reduced slightly by this procedure, the notch toughness is usually significantly enhanced because of the resulting fine grain size. The procedure works with both quenching and air cooling from the intercritical temperature, although the toughness enhancement is more apparent after quenching, and quenching also lessens the drop in the tensile strength.

It should be noted that this procedure does not work when the properties of an alloy steel depend on age hardening or transformation to martensite.

Heat Treatment Rigging

Handling of forgings through the heat treatment process can make or break the success of the operation. Just as care has to be taken in the choice of material and heat treatment procedure to obtain the required mechanical properties in a given component, then just as surely thought must be given to how to handle the part through the process. For example, small parts can be set up in baskets to facilitate loading into the furnace and transport from the furnace to the quench tank, but is it simply a matter of piling as many parts into the basket as it will safely hold? If the basket is piled up with forgings, is enough time being allocated for heating the charge, or was this reckoned simply on the size of the individual pieces? If sufficient furnace time has been allowed, how will the load behave in the quench tank—as if as a solid mass—or just as though the load was made up of individual well-spaced items? These aspects can have a significant effect on the results, and the test coupon provisions may not be representative of the load, depending on the disposition in the furnace and the quench tank. The heat treatment shop crew may not always be aware of the consequences of an overloaded furnace basket. Staying with the concept of a furnace basket for a moment, consider the situation where the components have been bored before heat treatment—and this is generally the desirable way to heat treat parts that are designed to have a bore—it might be expedient to lay them down in the basket to avoid them falling over, but when quenched, the bore might then be at right angles to the direction of quenchant flow and the bore surfaces might not then get quenched properly. This can cause uneven hardening, distortion, and possibly cracking. Unless the methods actually used were faithfully documented, and alas this is often not the case, an investigator might chase lots of esoteric theories in trying to correct an otherwise simple problem. Therefore, rigging a forging or forgings for heat treatment deserves careful thought and planning. There are two basic approaches to the handling of forgings in heat treatment. One is to use hot rigging, and the other cold.

Hot Rigging

As mentioned above in the case of a furnace basket or tray, hot rigging accompanies the part through the furnace and into the quench tank, and frequently through the tempering cycle as well. The rigging will provide a means of holding or supporting the forging in the furnace, transporting it in the desired orientation to the quench facility by crane, removing it from the tank, and proceeding through the temper cycle. The rigging will also accommodate any venting device that may be needed to permit the escape of trapped air or steam. This type of furnace rigging is particularly useful for heat treatment in a vertical furnace. Even for rigging that is to be used repeatedly, it may not be necessary to resort to expensive heat resisting alloys. Commonly available alloy bar and plate steels have been used to good effect to make heat treatment rigging. In one example the forge shop processed numbers of long SAE 4130 forgings that were subsequently trepanned, giving a supply of core bars that were used for heat treatment furnace rigging. As a word of caution, the rigging material should not be of high hardenability material, since this may crack after transforming. Distortion and scaling will usually determine its useful life, and that, in terms of hours at the austenitizing temperature, will fall far short of life determined by creep damage. However, the equipment should be inspected carefully between periods of use, and loads must be kept low. In *vertical furnace operation*, that part of the rigging used for hitching to the crane is arranged to be above the furnace door so that the crane hook can be engaged and support the load before the door is opened, thus reducing delays in removing the forging and proceeding to the quench tank. One such furnace door design uses compressed-air-operated, insulated split cast steel door shells. The furnace doors support the load until the time comes to open them, when the load is transferred to the crane.

The rigging may be made up from separate parts that are to a degree interchangeable. An example would be a thick base plate, or spider, through which a central stem is passed. The spider plate is retained by an integral boss at the bottom end of the stem. The stem could be passed through the bore of a long hollow forging and the piece blocked up clear of the spider plate to permit water flow up the bore, and ports would be provided in the spider plate as well to assist in cooling the bore. A distance piece located on the stem near the top of the bored forging would assist in keeping the part upright.

For solid block forgings to be treated in a vertical furnace, they could be blocked up off the base plate and chained around the stem using carbon steel chain held in place by a simple pin. Long solid forgings are often provided with a transverse hole drilled in a prolongation at one end. A steel pin is used to secure the forging to a clevis or fork, and an extension of this passes through the furnace door to carry the forging in the furnace. This system can be used also—but with care—for a bored forging, provided that the forging bore is not obstructed by the transverse support pin (such a situation could seriously impede the bore quench). Turbine and generator rotor forgings are heat treated vertically using a more sophisticated version of this rigging that enables the forging to be rotated during cooling, particularly if fast air quenching is required.

For long hollow bored forgings, such as tank gun barrels, forged in groups from a single heat of steel, it is desirable to make up economic furnace heat treatment loads by having several forged tubes in the same vertical heat treatment charge. One method of accomplishing this is by the use of a spider plate, similar to that shown in Fig. 9.2, in which holes have been drilled round the periphery, each large enough to accept the muzzle end prolongation of a gun barrel. Ample clearance is necessary round the muzzle where it passes through the plate and between the adjacent (larger diameter) breech ends. A central hole in the plate accepts a short stem that will pass through the furnace door to carry the load. The integral prolongation (that includes mechanical test material) at the muzzle end of each gun barrel is machined to provide a ring larger in diameter than the muzzle OD but capable of passing through the holes in the rigging support plate. The barrel muzzles are fed through the support plate and held in place by half rings fitted between the muzzle ring and the plate. Sufficient annular space must be allowed between the gun barrels and the furnace wall to ensure that they are hung within the furnace working zone, which is of course smaller in diameter than the furnace ID. In this way, the barrels are austenitized together, lifted from the furnace to the vertical quench tank, and vertically quenched with the bores unobstructed.

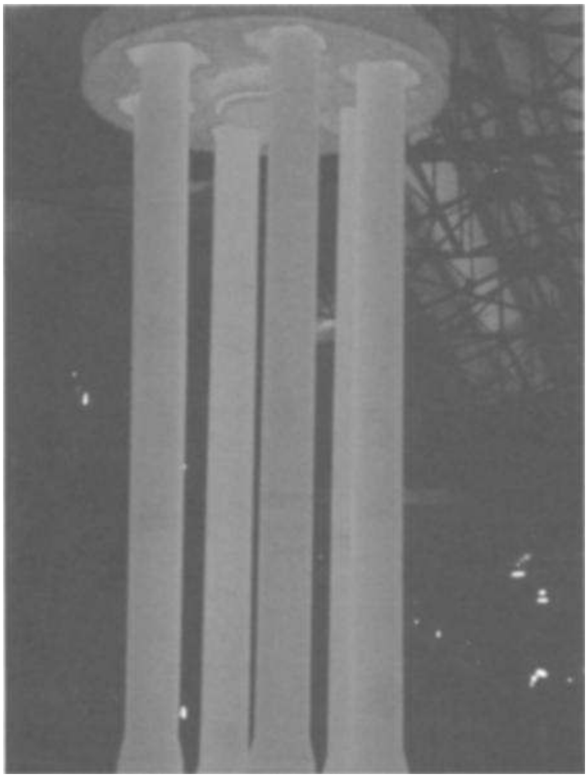

Fig. 9.2—A group of bored alloy steel cylinders about to be water quenched in a vertical tank. Notice the hot furnace rigging consisting of a bored spider plate and a central stem. The forgings were about 20 ft (6 m) in length. (Courtesy Ellwood National Forge Company)

In a vertical heat treatment procedure, when a preliminary normalizing cycle is to be employed, the use of the higher normalizing temperatures would be expected to cause excessive wear and tear on the rigging. In such circumstances, the normalizing part of the cycle could be done in a horizontal furnace, provided that the parts can be supported to minimize distortion. This also indicates that although heat treatment in a horizontal furnace would not be expected to require elaborate rigging, care must be taken to keep the furnace car refractories in a good state of repair and to provide adequate quality support for the furnace contents. These must not be permitted to rest directly on the furnace car refractories, but must be blocked up from it to allow free circulation around the forgings and promote even heating.

The foregoing gives some idea of the scope of the hot rigging used particularly in vertical furnaces; however, it should be noted that hot rigging used in the furnace is transferred to the quench tank and competes with the forgings in the business of heat extraction. In some instances, the combined weight of forging and rigging can deny the forging the best available quench. In such a situation, it may be necessary to look for an alternative way to support the piece in the furnace and take it to the quench facility.

An alternative hot rigging system uses austenitic 300 series stainless steel bails, made from bar stock of about 2 in. (50 mm) diameter, bent into a hairpin configuration, and welded with adequate preheat to the forging using a suitable austenitic stainless steel filler such as SAE Type 309. These bails are attached to discard material, such as a test prolongation. The forgings are hung in the furnace by means of a steel pin passed through the bail and attached to side plates, or for multiple pieces attached via the bail to a spider plate. An example is shown in Fig. 9.3. This also demonstrates the use of thermocouple pockets tack welded to the piece for temperature monitoring during heat treatment.

Figures 9.4 and 9.5 demonstrate, respectively, the use of rotor style hot rigging and twin-welded bales for the vertical heat treatment of 3.25 % Ni-Cr-Mo-V forgings for an offshore tension leg platform application.

Cold Rigging

As the name suggests, cold rigging is not heated in the furnace with the forging and is used to aid in transporting it from the furnace to the quench tank. This type of rigging is used widely in both horizontal and vertical heat treatment furnace practice. Some equipment is designed specifically for a particular forging design; others are adaptable to a wider range of applications and are supplied commercially rather than being made in house to suit particular needs. Typical of this kind of rigging is the lifting fork carried by a crane and inserted under the forging when the furnace door has been opened and the car rolled out. The loaded fork is taken to the quench tank and the parts are immersed. Forks can be used on irregularly shaped forgings like large crankshafts as well as cylindrical shapes when a tine is slipped into the bore.

A simple but effective use of cold rigging off the horizontal furnace car is the expedient of slipping a chain sling round a piece or pushing a bar through a bored hole and using chain slings on each side to lift it.

Large flat forgings like tube sheets require some thought before planning a quench. If the forging has no bore and especially if it is dished on one side, then picking it up flat off a furnace car and quenching it will result in steam trapping or blanketing on the underside. The forging needs to be presented to the tank at an angle, preferably vertical, although this is unlikely to be possible with horizontal quench tanks. This means having a special lifting rig and possibly having the piece inclined in the furnace. If the diameter permits, some tube sheets are hung vertically in a vertical furnace to accommodate this problem. The use of scissor type tongs, sometimes known as Heppenstall Tongs, set over the edge of a tube sheet can be used to lift and transport it at the correct orientation from a horizontal furnace car, to a vertical quench tank. Right angled brackets have been used to lift large rings from car to quench tank, and the large bore permits good water circulation. An example of this is shown in Fig. 9.6.

For large heavy cylindrical forgings, such as polyethylene reactor vessels for example, vertical heat treatment is preferred, but the weight of the forging and the associated

Fig. 9.3—Two pressure vessel shells to ASTM A 508 Class 2 being checked for temperature rise after water quenching. Note the use of type 316 austenitic stainless steel bar as support straps or bales when hanging the forgings in a vertical furnace. Also note the 1-in. (25-mm) tubes tacked to the OD to act as thermocouple pockets.

Fig. 9.4—Hot rigging, of the type sometimes used in the heat treatment of rotor forgings. Although this particular system would not permit the forging to be rotated during air cooling, this forging was to be water quenched. The forging is being loaded into a vertical furnace through the split cast steel door. This runs on wheels that can be seen in the foreground.

mass of a thick base plate and stem rigging could tend to jeopardize the quenching operation. A solution is to support the forging on a temporary fabricated stool in the furnace. The stool is substantial enough to bear the weight of the forging during austenitizing, but does not interfere with furnace atmosphere circulation. It remains in the furnace when the forging is removed. The quenching operation is achieved by dropping a cold stem into the vessel bore after opening the furnace doors. The stem is fitted with hinged fingers that drop open when they pass through the bore, Fig. 9.7, to engage on the bottom of the forging. Stabilizing fins may be provided on the stem also to prevent the forging tilting when it is lifted. Lifting is then begun and the forging is carried over to the tank. Since the rigging was cold, no excess heat is added to the quench load, and also since they are cold, the lifting fingers can be designed on the basis of their cold strength.

In talking of rigging, either hot or cold, mention must be made of the difficulties associated with quenching blind bored forgings. This is not an uncommon problem. If the vessel is quenched blind end up, the bore fills with the quench medium and essentially no bore circulation occurs after that. Severe bore cracking is the inevitable result. If the forging is quenched with the bore down, the bore partially fills with water and then the trapped air and steam pressure prevents the cavity from filling completely. Bore cracking is again inevitable. If the cylinder is quenched horizontally, the bore fills but air and steam still tend to get trapped and cracking and soft spots result. The solution for vertical quenching is to orient the piece so that the bored end goes into the quench first, but the forging is fitted with a U-shaped vent tube, Fig. 9.8, and is austenitized in the inverted position. The vent tube must be placed so that the end is close to the blind end of the vessel. The outer end of the U-tube must extend beyond the bottom of the vessel so that when immersed in the tank the tube end projects above the surface in the quench tank. When the forging is quenched, the trapped air in the bore exhausts through the vent tube followed immediately by a plume of steam and water. For a large forging, this jet can reach a height of over 20 ft (6 m) and drench any unfortunate bystanders on the wrong side of the tank! For horizontal quenching, Fig. 9.6, an L-shaped vent tube serves a similar purpose, although the initial jet may not be quite as spectacular. It should be noted here that the tube bends should be made using a tube bender or welding fittings. The use of threaded malleable iron fittings for the U-section will not work, since these crack on first hitting the water and stop the venting action. Austenitic stainless steel tubing is ideal for this purpose.

Another aspect of a multistage heat treatment cycle that is not always taken into account is the timing of the various stages. As mentioned previously, applying a normalizing treatment ahead of the austenitize and quench treatment can yield significantly improved heat treatment response. This is frequently used on high hardenability materials. The normalizing stage could be done in a different furnace or even in another heat treatment facility from the one where the austenitize, quench, and temper cycle will be run. Furnace scheduling can come into play, and it may be expedient to delay the start of the next austenitizing cycle by a few days. This can have drastic consequences in the form of cracking that is found after quenching and tempering. The problem was not caused by quench cracking, but by the effect of irregular residual transformation stresses in the as normalized material. This was experienced in nickel-chromium-molybdenum-vanadium forgings, and metallographic exam-

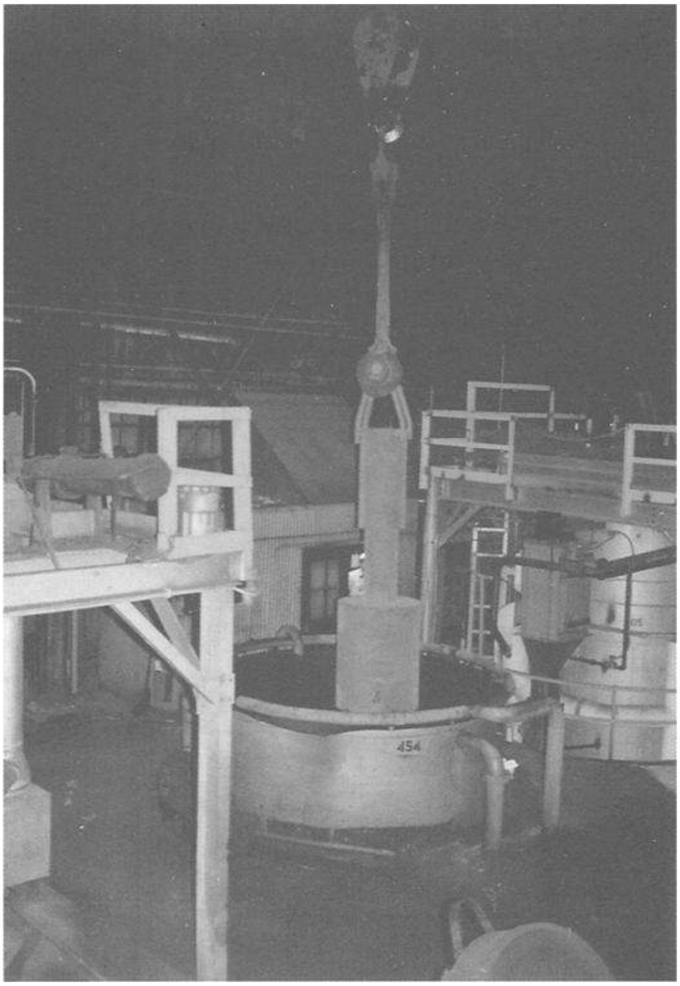

Fig. 9.5—A similar alloy steel forging to that shown in Fig. 9.4, but fitted with two type 316 austenitic stainless steel bales to reduce the heated weight and keep heat treatment rigging clear of the forging. A compressed air cylinder used to operate the vertical furnace doors is visible to the left foreground.

ination showed, by the presence of decarburized crack surfaces, that the cracking was either present before or occurred during the heating period for the austenitizing stage before quenching. The fix was to commence the austenitizing stage within about 12 h of cooling from the normalize, or if that was not possible to endure the cost of a short tempering stage after normalizing.

It will be seen then that by following a common sense approach and by keeping some basic principles in mind, most heat treatment problems can be prevented by careful planning, or solved if by chance they are encountered the hard way. A short list could include:

A. Heat Treat	B. Material Used	C. Forging Size	D. Requirements
Cycle Mandated Or Producer's Choice?	Chemistry & Manufacture	Weight & Shape	Specification Properties

For an austenitize, quench and temper cycle water is the preferred quench medium, since this can usually be expected to give the best mechanical properties with the minimum of environmental problems.

The steel chemistry to be used may dictate the choice of quench medium, bearing in mind the carbon upper limit of 0.35 % for safe water quenching. The steel hopefully has been vacuum degassed and made to a clean steel practice. However, when the steel has not been melted and prepared for a particular forging application, and available stock must be used, the heat treatment cycle must be adjusted accordingly. For example, SAE 4330 is not considered to be a Standard Grade and is not included in ASTM Specification A 29/A 29M. The forging manufacturer may then have to use SAE 4340 and adjust the heat treatment accordingly.

If left to the choice of the producer, the choice of horizontal or vertical furnace may be based on furnace availability, but the shape, form, and weight of the forging should enter into this particularly with regard to distortion risks and venting. If the forgings are amenable to heating in a horizontal furnace, there may be economies in scale to be gleaned by heating several forgings in the same furnace load and quenching them singly or in small groups, the furnace car being run back into the furnace and kept under heat until the load has been quenched. Sometimes two furnaces are useful for this type of operation, the quenched forgings being loaded into the second furnace for holding preparatory to the temper cycle.

The specification may require that a certain type of heat treatment furnace, a vertical unit for example, be used. In this instance the choice is made. Occasionally, the specification may require the use of a specific quench medium, oil for example, regardless of the composition. This can be particularly onerous if additional mechanical property requirements are needed, beyond the limits of the original specification. This kind of dilemma must be addressed at the inquiry and order stage, rather than when the parts are ready to heat treat! For some government procurement, this can pose a problem since taking exceptions can make the bid nonresponsive. As an example, a particular specification that called for a normalize and temper heat treatment cycle for an alloy steel was specified for a large frequently purchased component. In order to obtain the necessary mechanical properties, experience had shown that it was necessary to quench and temper the forgings. This need was understood and the accepted path was to bid the order without exception and then request a deviation on the heat treatment after the order was awarded. However, one has to be sure of one's ground before accepting a situation like this!

Tempering

Although there is often some flexibility in choosing the optimum austenitizing temperature for a particular steel composition and forging, the requirements for tempering are more demanding. There is usually a fine balance between meeting the required minimum tensile and yield strengths, and optimizing ductility and toughness. This means close furnace temperature control and attention to the required tempering time. Cooling from the tempering temperature is also important. Commonly this is done in air to avoid the expense of tying up the furnace for a slow cool, and this can

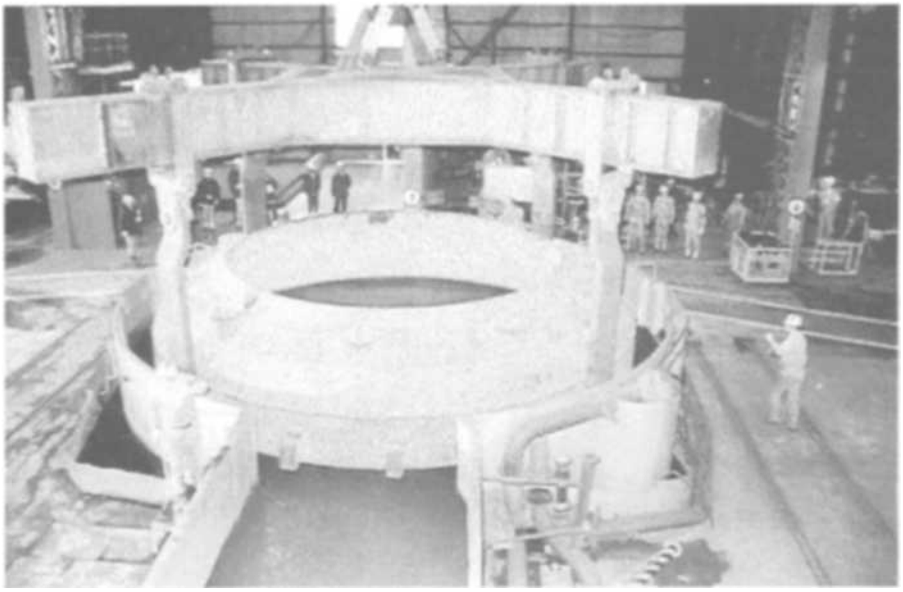

Fig. 9.6—Use of cold rigging, i.e., not heated in the furnace with the forging, to lift and support the very large nuclear forging from the furnace to the quench tank. (Courtesy of the Japan Steel Works, Ltd.)

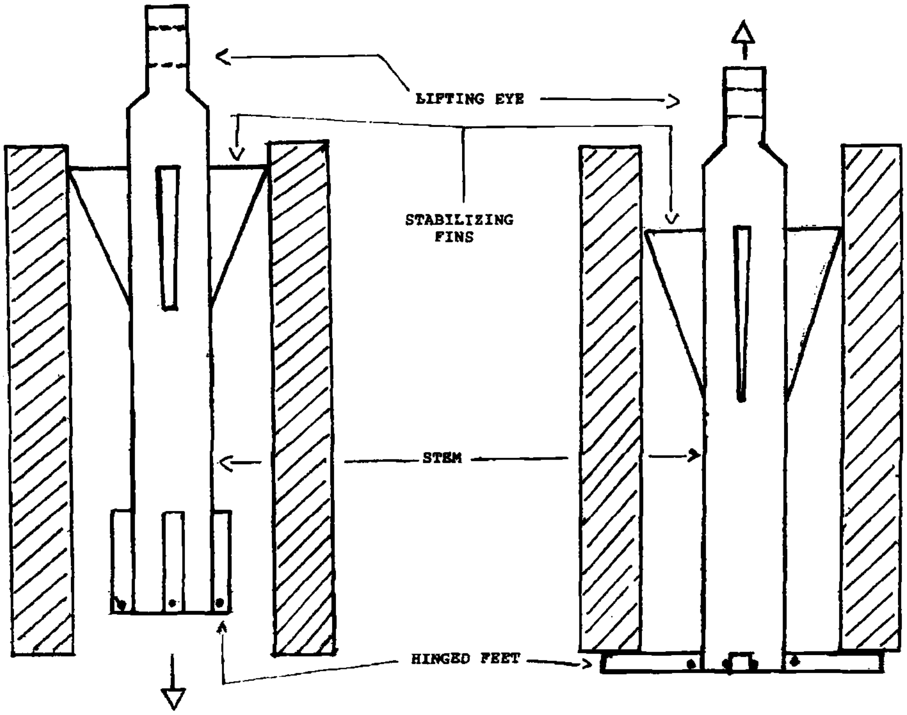

Fig. 9.7—An example of cold heat treatment rigging that could be used to lift a long and heavy forged cylinder from a vertical furnace. The stem is dropped through the bore until the hinged feet clear the bottom of the forging when they drop down enabling the forging to be lifted quickly. The upper fins help stabilize the stem at the center of the bore, but do not obstruct coolant flow through the bore during quenching. The fixture does not need to be designed to withstand the furnace temperature.

minimize time spent going through embrittling temperature zones for susceptible materials. The specification may require that the forging be quenched from the tempering temperature for this reason. This has been a requirement for some weldable nickel-chromium-molybdenum alloys such as HY-80 in military specifications. Caution is required, however, when machining is carried out after quenching, because if stock removal is asymmetrical unacceptable distortion may result. An example of this was seen in the machining of a large structural forging in HY-100 nickel-

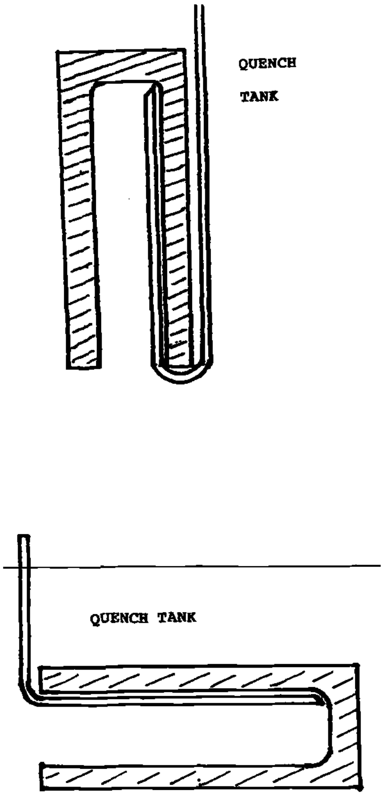

Fig. 9.8—Sketches showing the use of vent tubes during quenching. The U-tube is used during the vertical quenching of blind bored forgings to vent steam and air from the bore. One end of the tube must be positioned close to the blind bore end face and the other maintained above the level of the quench medium, at least during the early stages of the quench. For the horizontal quenching of a blind bored cylinder, the vent tube is L- shaped.

chromium-molybdenum alloy steel, similar to Grade 4N of Specification A 508/A 508M, Quenched and Tempered Vacuum-Treated Carbon and Alloy Steel Forgings for Pressure Vessels. The forging was made as a large diameter disk, about 20 in. (500 mm) thick. In order to assure full volumetric ultrasonic examination, the forging had been bored before a heat treatment cycle that included water quenching after tempering. The final machined configuration included a square counterbore on one side. While this was being done in a vertical boring machine, the forging warped severely as the counterbore was being formed. Since quenching after tempering was mandatory, change in manufacturing procedure was necessary to include the counterbore before heat treatment, and to revise the ultrasonic examination procedure accordingly.

Rapid cooling after tempering results in high residual stresses in the forging, and since these are compressive at the quenched surface and so helpful in improving fatigue strength, this method has been proposed for improving the fatigue strength of axles for railroad applications [3].

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10

Mechanical Testing

BEYOND HEAT TREATMENT CYCLES SUCH AS spheroidizing that are used to enhance machinability, the primary reason for heat treating a forging is to establish certain minimum strength properties in the component. This cycle is referred to in different ways. It may simply be Heat Treatment; Final Heat Treatment; Heat Treatment for Properties; or as is used expressively in Europe, Quality Heat Treatment. The latter has an air of confidence about it, and certainly anyone doing any heat treatment at all would like to think that their work has quality.

When a forging is specified, certain minimum mechanical properties are anticipated. These may range from simply a surface hardness value to tensile, ductility, and toughness characteristics, as dictated by the design criteria. The chosen material specification will be critical in establishing the likelihood that the design requirements will be met.

Essentially the same material at the same strength level can show up in several specifications written for specific applications that differ in scope. Some knowledge of the history behind the individual specifications can be useful in understanding why they were written and why in some cases the expectations far outshine the realities. This will be looked at in more detail later, but a brief example here might be helpful in illustrating the mechanical testing aspects.

Often for plain carbon steels the same grade can be found in a number of forging specifications with heat treatment being an important variable. In the following list of ASTM specifications the heat treatment requirements are contracted to:

At first glance, most of these specifications for carbon steels have the same requirements, but some study will show that there are significant differences that influence cost and quality. The use of small quantities of alloying elements is a distinguishing feature, and the heat treatment together with mechanical testing requirements and frequency are linked with the scope descriptions.

Despite having Charpy impact testing as a requirement, flange forgings made to Grade LF2 of Specification A 350/A 350M, Carbon and Low-Alloy Steel Forgings, Requiring Notch Toughness Testing for Piping Components, have been the subject of complaints worldwide for failure to exhibit the required notch toughness, and some changes have been made to try to address this problem. Some failures were traced to fraud, but some were attributed to the mechanical testing requirements. A detailed critique of this specification will be addressed later.

The cost of forgings tends to rise with the mechanical testing complexity of the specification, but of course, the assurance that the forging has acquired the required properties rises as well.

Most forging specifications require that tension tests be taken at a midwall location in hollow or bored items and at the midradius or quarter thickness location in solid components. It will be appreciated that the condition of a forging has an important influence on the post-heat treatment mechanical properties:

A = Anneal, generally intended to be a full, not subcritical anneal
N = Normalize
NT = Normalize and Temper
QT = Quench and Temper

Specification ASTM No.	Grade/ Class	Tensile/Yield Strengths ksi/MPa minimum	Impact Test Yes/No	Heat Treatment A; N; NT; or QT
A 105	N/A	70/36 [485/250]	No	A; N; NT; or QT*
A 181	Cl. 60	60/30 [415/205]	No	not required
A 181	Cl. 70	70/36 [485/250]	No	not required
A 266	Gr. 1	60/30 [415/205]	No	A; N; NT; QT
A 266	Gr. 2	70/36 [485/250]	No	A; N; NT; QT
A 266	Gr. 4	70/36 [485/250]	No	A; N; NT; QT
A 350	Gr. LF1	60/30 [415/205]	Yes	N; NT; QT
A 350	Gr. LF2	70/36 [485/250]	Yes	N; NT; QT
A 707	Gr. L1	66/52 [455/360]	Yes	A; N; NT; QT
A 707	Gr. L2	66/52 [455/360]	Yes	A; N; NT; QT
A 727	N/A	66/36 [414/250]	No**	N; NT; QT
A 765	Gr.1	60/30 [415/205]	Yes	N; NT; NNT; QT
A 765	Gr.2	70/36 [485/250]	Yes	N; NT; NNT; QT

*Heat treatment for forgings to A 105/A 105M is mandatory only when certain pressure rating and size categories are exceeded.
** Forgings to A 727/A 727M are expected to have inherent notch toughness.

- Are the permitted alloying elements present?
- Is the part bored in its final condition?
- Was the part bored before the quality heat treatment?
- Was a significant amount of stock machined off the part after heat treatment?
- What type of quality heat treatment was used?
- What provision was made for mechanical test material?
- How much and what type of mechanical testing is required?
- What is the required frequency of mechanical testing?

All of these items have an impact on the manufacturing costs for the forging, including the hidden costs for possible reheat treatments, retesting, and replacement.

How then are forgings tested for mechanical properties and how does this vary from specification to specification?

ASTM writes and maintains an extensive list of Standard Test Methods and Practices that describe various methods of hardness, tension, bend, impact, and fracture toughness testing that are applicable to steel. The most frequently used of these are referenced in an important specification, A 370, Standard Test Methods and Definitions for Mechanical Testing of Steel Products. This standard is maintained by ASTM Committee A01 on Steel, Stainless Steel and Related Alloys, and is referenced in all of the steel product specifications.

Hardness Testing

Hardness has always been a criterion for the strength of steel with resistance to marking by a file often being used as a rating system. The simplest form of mechanical testing is the hardness test with requirements listed as a minimum, maximum, or range in a familiar scale such as Brinell, Vickers, or Rockwell. The most commonly used system for steel is still the Brinell test, developed by Swedish metallurgist J. A. Brinell and announced in 1900. His test relates hardness to the area of the impression left by a 10-mm diameter hardened steel ball under an applied static load of 3000 kg. This test is the basis for Test Method E 10 Brinell Hardness Testing of Metallic Materials, first published in 1924, about a year before the inventor's death.

Some minimum number of hardness tests on a forging may be required, but there may be few other requirements. It should be remembered that this is a surface test and is strongly influenced by decarburization during heat treatment. If the part has been machined after heat treatment, then this is unlikely to be a factor, but equally if much surface stock is removed after hardness testing, the actual hardness may be appreciably lower than that recorded. This will depend both on the size of the heat treated cross section and the material. Hardness testing, as the only test of mechanical properties, can give some indication of the material tensile strength from the approximate conversion tables found in Specification ASTM E 140, Hardness Conversion Tables for Metals, and show that the forging was in fact heat treated; but even this has to be approached with caution. Quite a few years ago, when large aircraft were powered by piston engines, a particular design of two row radial air cooled engines used a crankshaft built up from three forged parts, the shaft itself with an offset center bearing journal section, the front counterweight with an integral stub shaft, and a rear counterweight with an auxiliary drive shaft. The crankshaft was built up by means of a split collar on each counterweight forging. These facilitated clamping the counterweights to the crankshaft by means of a pair of large high strength fitted bolts. The counterweights and shaft were closed die forgings in a SAE 4340 type of steel, and were oil quenched and tempered in heat lot batches together with representative test blanks for tension and Izod impact tests. The crankshaft assembly involved carefully measuring the bolt extensions as they were being tightened. A problem cropped up when, apparently, a front-end counterweight clamp was observed to be collapsing during the bolting process. Investigation showed that the counterweight was soft, far below the minimum hardness limit, except for a small area near the counterweight heel at the opposite end to the clamp location. The conclusion was that the forging had not been heat-treated. The counterweights were purchased in the heat-treated condition from the forge shop, and all were subject to receiving inspection including Brinell hardness testing.

The counterweights being heavy stubby pieces, were difficult to handle. The receiving hardness testing procedure was to support the forging by a sling and place the Brinell impression near the heel—the very location that did meet the hardness requirements. Investigation at the forge shop showed that they tested the forgings in the same location. It was noted that the forge shop floor near the closed die drop hammer was covered with steel plates, and after removing the forging flash, the counterweights were laid on the plates with the heel location and the stub shaft touching the steel floor plates. Evidently, the floor plate acted as a heat sink and quenched the counterweight heel leaving a locally hard surface. Why the part missed the heat treatment load was not determined, but hardness-testing requirements were significantly overhauled afterwards!

In Specification A 370 the Brinell and Rockwell hardness tests are included. Reference is made to Test Method E10 for the Brinell test, since Brinell hardness numbers are commonly used in ASTM steel specifications, and it is noted here that the tungsten carbide ball is now mandatory for this test. The Rockwell and Vickers tests are less frequently specified in the ASTM steel specifications, but nevertheless these are important hardness testing methods, particularly in conjunction with quality heat treatment and surface hardening. Test Method E 18, Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials, is referenced for the various Rockwell hardness testing methods. A feature of the Rockwell tests is that a preload is used to stabilize the component in the machine before the required full load is applied. Instead of measuring the area of the impression, the depth that the indentor penetrates into the test surface is measured. The Vickers diamond pyramid hardness test, Method E 92, Vickers Hardness of Metallic Materials, is a very accurate indentation hardness testing system that uses loads ranging from 1 to 120 kg, depending on the application. The higher loads, for a given material give larger impressions that increase the reading accuracy. The measurements are made across the points of the diamond shaped impression using the built in microscope. In the writer's opinion, this is probably the most accurate of the hardness testing systems, and although commonplace in Europe, the system was never very common in North America. A typical Vickers hardness tester is shown in Fig. 10.3.

Tension Testing

The tension test is one of the most commonly specified mechanical testing options for steel forgings. There are three basic test approaches:

1. Take test specimens from a separately forged test bar.
2. Take the test specimens from a sacrificial component.
3. Use material provided integrally as a prolongation, as in an extension of the forging length or outside diameter, or from material that is to be removed to provide for an opening in the component, such as valve port in a pump barrel. The use of a prolongation is the common approach in vessel forgings, made to Specifications A 266/ A 266M and A 508/A 508M, for example.

The use of a separate test bar is permitted in several forging specifications, but the rules for this are more restrictive in some than in others. While the test bar may have to be heat-treated in the same furnace load as the forgings it represents, there probably are size differences that should be considered for quenched forgings. It is not uncommon for forgings to be taken from a furnace and quenched individually. The difference between quenching large forgings weighing perhaps 2000 lb (900 kg) each and a test bar weighing appreciably less than 100 lb (45 kg) weighs heavily on the side of the test bar.

The concept of prolongation discard from the quenched end of a forging deserves a few words. For annealed or normalized forgings—and up until the time that awareness of brittle fracture prevention became common, this was about the only heat treatment option for pressure vessel materials—it was considered to be unnecessary to limit the proximity of a tension test specimen to the heat treated end face of a forging. Since quenching is associated with forming transformation products such as martensite and bainite, it can be appreciated that for any given steel there is a limit on hardenability and hence the section size that can be through hardened. The distance from a quenched surface to the test location, therefore, assumes great importance. The need for lowered ductile/brittle transition temperatures that was expressed from about the mid-1960s onwards introduced the acceptance of quenching and tempering for other than enhancing tensile strength and hardness. To get a good representation of the strength and toughness properties of the quenched and tempered forging, the distance of the test specimens from the quenched end has to be taken into account.

In Specification A 508/A 508M, written originally to cover forgings for use in nuclear reactors, the heat treatment specified for all of the grades is to quench and temper, and it was not uncommon for a normalize, quench, and temper cycle to be used especially for large heavy section forgings, such as reactor vessel closure flanges, shell courses, and nozzles. Since the applications were regarded as being highly critical, great care was taken in writing the specification to give the best assurance that the required properties were indeed obtained from the forging. This, in turn, can be expressed as uniformity throughout the forging, and that implies uniformity in chemical composition, forging, and heat treatment. Specification A 508/A 508M approaches this requirement by mandating that the steel be vacuum degassed, that the forgings be quenched and tempered, and by specifying a greater number of tests as the forging size increases. Overall length of the forging is also considered so that for longer pieces testing has to be done at both ends. There are two main reasons for this provision, one is to look at quenching uniformity, and the other to take into account possible carbon segregation that is sometimes found between the top and bottom of large ingots. This can be great enough to affect noticeably the tension test results.

In turbine and generator rotor forgings, *Radially* oriented test specimen cores are usually taken between adjacent wheels in turbine rotors or from the winding slots in generator rotors. Another factor in considering tension tests is the test orientation. As a general rule of thumb, the ductility measurements in tests taken from wrought material are better when the test specimen axis is parallel to the hot working direction, known as *Longitudinal Testing*. These properties may deteriorate when the specimen is taken at right angles to the working direction in what is referred to as *Transverse Testing*. In hot rolled plate there is a third test direction taken through the plate thickness, known as *Short Transverse Testing*.

Differences in tensile ductility, measured as elongation and reduction of area, are largely caused by the effects of nonmetallic inclusions in the steel. Increased numbers of inclusions will accentuate the ductility differences between the longitudinal and transverse directions. Alignment and elongation and spreading of inclusions parallel to the direction of hot working are the major sources of these directional property differences. In rolled plate the inclusions, particularly the sulfide and silicate type, can be rolled out as extremely thin plates with relatively large surface areas, known as laminations, and it is these that are the cause of short transverse ductility and strength problems. In forgings, because of the method of hot working the sulfide inclusions tend to be cylindrical in shape, and typically tapered at the ends, cigar fashion, and the silicate types are strung out in length. The alumina type inclusions are more refractory and tend to appear as aligned, broken, angular particles.

In some applications the transverse ductility in a forging can be related closely to performance and the specification will require that tension testing be done in that direction. Artillery gun barrels are an excellent example of this. During firing the gun barrel bore is exposed to fluctuating heat and internal pressure, conditions ideal for fatigue cracking, and it is this problem that primarily dictates its safe working life—safe that is for the gun crew. The specification will require transverse tension tests (oriented tangential to the bore) to be taken from prolongations of both the breech and the muzzle. Aside from the minimum strength (yield strength usually) the ductility requirement is stipulated as a minimum reduction of area percentage. This measurement is not colored by proximity to gage marks, and is responsive to steel cleanliness, hydrogen content, and heat treatment.

The problem of test property directionality in forgings can be tackled from three aspects, hot working, steel cleanliness, and inclusion shape.

Tackling the cleanliness aspect first, while it is true that alignment of inclusions adversely influences transverse ductility, sheer numbers of inclusions will also adversely affect the longitudinal ductility and strength as well. As the volume of inclusions is reduced, the difference between transverse and longitudinal ductility eventually begins to narrow, as in the case of highly refined double vacuum melted steel, where there is little significant difference between the longitudinal and transverse ductility even when the hot working reduction ratio is of the order of 20: 1 or more. This trend is clearly seen in high quality basic electric, ladle refined, and vacuum degassed material with sulfur levels lower than 0.002 % and phosphorous contents below 0.010 %, and such steels are commonly available for making forgings today. Another approach, often used in conjunction with ladle refining, is to use inclusion shape control [1] to render inclusions more innocuous in their effect on mechanical properties. This is done by modifying the inclusions at the end of the steel making process by the addition of an element such as calcium. The object is to make the inclusion into a stable spherical shape that will be maintained through hot working. The calcium—and this is the element principally used for the purpose—forms a stable calcium-aluminum oxide compound around the manganese sulfide and silicate inclusions, rather like a hard sugar coating around a piece of chocolate. The spherical particles resist deformation during the subsequent hot working operations. They are classified as globular inclusions. These small globules do not have much adverse effect on transverse ductility, and so assist in making the steel acceptable for applications such as artillery gun barrels and pressure vessels. The use of calcium for inclusion shape control tends to be frowned on for bearing steel applications.

The effects of hot working and steel cleanliness tend to be interwoven, and it is worth repeating some of the forging concepts here in the context of mechanical testing.

Judicious choice of ingot and forging practice can produce a forging that is essentially isotropic, if the design permits. This is achieved by having more or less equal hot work done in all directions, and can be found in some hollow forgings or stubby shapes.

A steam turbine rotor forging typically consists of a relatively short, large diameter body section where the rotor wheels are located, and integral arms or journals at each end for bearings and couplings. The arms are significantly smaller in diameter than the body, but may have appreciable length. Good properties in the radial direction are required for the turbine wheels, since they rotate at very high speeds and have to carry the turbine blades, so that the centrifugal forces are high. The journals are subject to bending loads, so that good properties are required in the axial direction. In order to get the optimum radial or transverse properties in the rotor wheels, the forging must be upset at some time during the forging procedure. This is frequently a specification requirement. As mentioned in the discussion on forging quality, the smallest ingot that meets the equipment and required weight criteria is chosen, since this minimizes segregation effects. The rotor body diameter is obtained by drawing back to size from the upset, such that the directional hot working obtained during upsetting is maintained giving the good radial properties in the turbine wheel section.

When making a hollow forging, the upsetting work is followed by hot trepanning to remove the original ingot core, and the bore so formed is expanded over a mandrel to the required size. The piece is then threaded over a water-cooled mandrel and lengthened by forging between the top die and a bottom V-die to the required size, all the time being rotated. The intent is to reduce the wall thickness by at least half in the process. In this case provided the axial extension of the forging is not excessive, the tensile properties are usually isotropic in all three directions.

The yield strength is measured from the tension test. At one time, for the carbon steels the requirement was to record the yield point, because many of these steels exhibited a distinct increase in strain without an increase in stress. However, some carbon steels, and most alloy steels, do not give this sharply defined yield point, and for these the Yield Strength is defined in Specification A 370 as the stress at which the material exhibits a specified limiting deviation from the proportionality of stress to strain. The offset method for determining yield strength is described fully in Specification A 370 and is specified for practically all of the ASTM steel specifications.

Aside from strength, ductility is a most important engineering feature of steel and features importantly in its reliability. This is measured as a percentage of the gage length of the tension test specimen. In North America the gage length for the standard round specimens is taken as 4 X D, where D is the diameter of the specimen. In Europe the gage length is 5 X D. Since a great deal of the extension in the tension test occurs close to the fracture where the specimen necks down prior to breaking, the elongation value from the 5D requirement is appreciably less than for 4D. In the test reporting the location of the fracture relative to the gage marks is helpful in assessing the elongation value, particularly in the case of marginally acceptable results.

Reduction of Area is another ductility value obtainable from the tension test. This is expressed as the difference between cross-sectional area at the fracture and the original area as a percentage of the original cross section. In some product form proposals, in order to facilitate automated tension testing, the reduction of area measurement may be dropped as a specification requirement. In the case of forgings, however, the reduction of area measurement is as important as elongation in assessing the results of the tension test. As an example, Fig. 10.1 shows three fractured tension

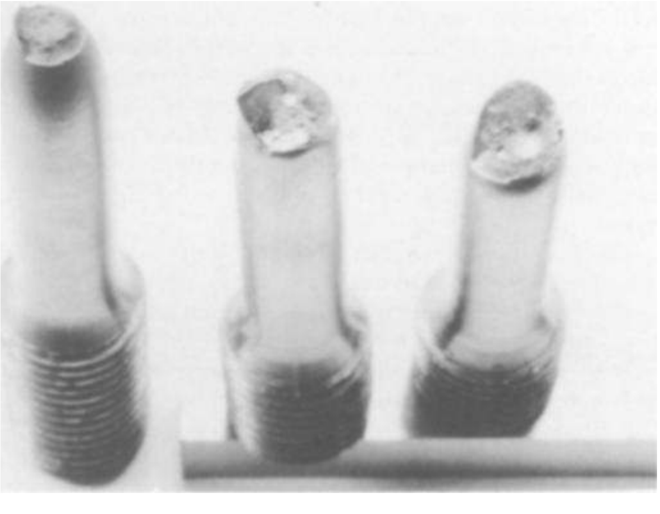

Fig. 10.1—Two examples of "Fish Eyes" in tension test fracture faces. These fracture abnormalities are caused by the presence of hydrogen in the steel. Typically the elongation and reduction of area values are reduced when fish eyes occur in the fracture. The effect on the reduction of area is evident from the third specimen from the same forging that was baked at 500°F (260°C) before testing.

test specimens, one exhibits a feature known as a "Fish Eye" and gave low elongation and reduction of area values. The other two samples from the same forging received a bake cycle at 500°F (260°C) for 1 h before testing, and gave normal elongation and reduction of area results. The low temperature treatment permitted some hydrogen to diffuse from the samples, and this effected the ductility improvement. Such bake cycles are permitted by Specification A 370, Test Methods and Definitions; however, consideration should be given to applying an equivalent bake cycle to the forging. An effort to delete the reduction of area measurement for forgings is likely to be strongly resisted.

Impact Testing

The full significance of impact testing probably was not realized in general industry until the early 1940s with the Liberty ship hull brittle failures, although the failure mode had been observed previously in storage tank and pipeline failures. Certainly, impact testing of alloy steels for use in aero engine components was commonplace more than ten years earlier, and the writer observed about 50 years ago that higher room temperature Izod impact test values were obtained from alloy steel heats that had lower phosphorous levels.

Two major impact tests were in use: both used similarly sized specimen cross sections and V-notches, and some machine designs allowed for testing both types of specimen. The methods were the Izod and the Charpy tests. The Charpy test was developed in France and the Izod, until after World War II, was almost exclusively used in Britain. The difference was that in the case of the Izod test the specimen was firmly clamped vertically in a vice at the level of the notch and was struck above the notch by a swinging pendulum. The energy absorbed in the test was registered on a scale. The pendulum had a force of 120 ft·lb (165 J) at the point of impact. The significant drawback to the Izod test is that it is difficult to run the test at other than room temperature.

In the Charpy test the notched specimen is supported on either side of the notch, and the pendulum strikes the specimen directly behind the notch. Again the energy absorbed in breaking the specimen is measured from a scale. Testing at temperatures other than ambient is relatively simple, provided that a means of cooling or heating the specimen is available. In steels an important characteristic is that the absorbed energy will fall steeply at some temperature known as the transition (from ductile to brittle behavior) temperature. The temperature at which this occurs depends mainly on the steel composition and heat treatment. To establish the transition temperature it is necessary to run a series of impact tests at different temperatures, and since the Charpy specimen only need rest on the supports for a very few seconds, changing the specimen temperature and running the test is very easy.

Brittle failure is a catastrophic very fast fracture that can run for very large distances, and there have been spectacular hydrostatic test failures of pressure vessels and pipelines from this cause. Figures 10.1 and 10.2 are examples of fast fracture. It is not surprising then that Charpy impact testing in accordance with Specification A 370 is a requirement in many ASTM steel forging specifications, and for the carbon steels at least has been the cause of much grief.

An unorthodox heat treatment procedure [2] involves partial austenitization in the region between the lower critical (a_{c1}) and the upper critical (a_{c3}) temperatures, followed by quenching and usually tempering. At the expense of a slight loss in tensile strength, the grain size is reduced significantly, giving improved Charpy impact test results. The method has been shown to be applicable to section sizes over 20 in. (500 mm). This heat treatment is included as an option in Specifications A 350/A 350M and A 266/A 266M. It is also permitted in Specification A 508/A 508M for Grades 1 through 3A.

Fracture Toughness Testing

Associated with the brittle fracture problem some other more involved—and more expensive—fracture toughness tests have evolved. Probably the first was the *Drop Weight Test* developed by Pellini at the Naval Research Laboratory as an outcome of the Liberty ship research, and is covered by ASTM E 208, Test Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels. On a frequency of use basis this is probably the most often used test after the Charpy impact test. The method is to deposit a weld bead of a brittle material (usually some hard facing weld metal) along the length of a block of heat-treated test material. The weld bead is notched by sawing at midlength to act as a crack starter location. The specimen is cooled to some predetermined temperature T and is placed, weld bead down, on an anvil. A weight is dropped from a height of about 5 ft (1.5 m) onto the back of the specimen, which is then examined. If a crack has extended from the weld fully across the specimen or has reached only one edge on one side of the weld, the test is declared to be a "break." Two more specimens are broken at a temperature of T + 10°F (T + 6°C) and if neither of these is classified as a "break" (i.e., "no-break") the Nil Ductility Temperature is declared to be T. Although few ASTM material specifications call for the drop weight test in Test Method E 208—it is covered by a supplementary requirement in Specification A 508/A 508M—the test has been part of the fracture toughness requirements for nuclear pressure vessel components in Section III of the ASME Boiler and Pressure Vessel Code for many years.

Other more specialized fracture toughness tests have been developed and some of these can use full section thickness test pieces. A fatigue crack of a controlled size is generated at the base of a machined notch and the Crack Tip Opening Displacement (CTOD) at the required test temperature is measured as the specimen is bent. Unstable fracture is not accepted before a given minimum CTOD value has been achieved. This type of test has been actively used for forgings intended for use in offshore tension leg oil platforms both in the Gulf of Mexico and the North Sea. While valuable for critical designs, this kind of fracture toughness testing is expensive in terms of providing the necessary test material, test equipment, and time to perform.

Fatigue Testing

Although not a formal part of any of the forging product specifications, very many forgings are designed for use in applications where fatigue is the primary failure mode. The examples of this are not hard to seek, when mechanical com-

Fig. 10.2—Brittle failure of a fabricated high-pressure water-tube boiler drum during initial hydrostatic test. Origin was a large undetected crack at the toe of a nozzle weld that occurred during the post weld heat treatment cycle.

ponents such as axles, propeller shafts, turbine and generator rotors, crankshafts, connecting rods, gears, and pinions that operate under high cycle fatigue conditions, and pump bodies and pressure vessels that endure low cycle fatigue conditions are routinely specified as forgings.

The fatigue strength of materials can be determined by the use of tests such as ASTM E 606, Standard Practice for Strain Controlled Fatigue Testing, but these are not included in the product specifications since the basic material characteristics in fatigue are known to the component designers, and the actual performance of a service involving fatigue is as much a function of the design of the part as the material, its heat treatment, and most importantly the surface treatment and finish.

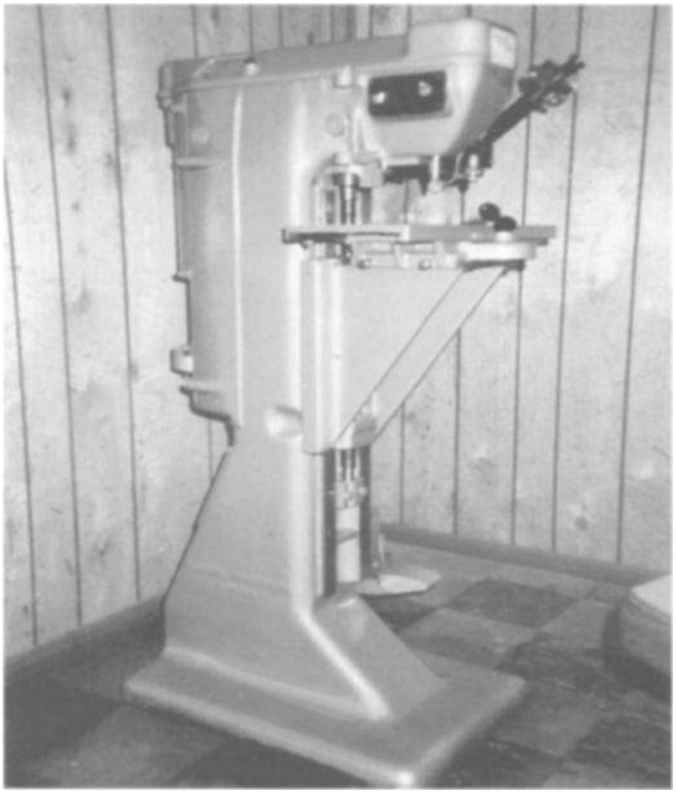

Fig. 10.3—A Vickers Diamond Pyramid hardness testing machine with sliding table and microscope with micrometer measuring device. The load range is 1–120 kg. Although very accurate, this type of floor hardness tester is difficult to use for other than small parts. A similar situation applies for bench Brinell and Rockwell hardness testers.

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11

Nondestructive Examination

AN IMPORTANT ASPECT OF QUALITY FORGING production is that the forging, having been shown to be made from the specified material, heat treated as prescribed and demonstrated to meet the mechanical property requirements, is free from material/process related conditions that might adversely affect its performance during use, in other words that the forging is sound and is what it appears to be. It should be recognized that some potential service pitfalls can be mitigated by the use of appropriate nondestructive examination methods, while others cannot. For example, magnetic particle examination of the critical surfaces of a crankshaft is most valuable in finding indications that could lead to a fatigue failure, but no nondestructive examination of the original plate would warn of a potential brittle fracture problem stemming from a badly designed deck hatch corner in the deck of a ship whose hull plates were being operated close to or below their transition temperature.

For steel forgings there are two nondestructive test approaches, one concerned with the finished surfaces, and the other looking at the volumetric quality.

Surface Examination

Visual examination is the simplest method of surface examination, and while other systems are important, the trained eye, perhaps aided by a low power magnifying lens is unquestionably the most important. Visual examination should precede any other surface examination, and should not be forgotten during any remedial work.

Magnetic particle examination is a commonly used method for surface examination of ferromagnetic forgings, and this method is further defined by the method of magnetization.

Eddy current systems are frequently used in automated systems for products, such as seamless or welded tube, and are used in some inspection lines for large-scale production of small forgings. They can be used for both ferritic and austenitic steels.

Another frequently used method is the liquid penetrant system, and for this the material does not have to be ferromagnetic.

Visual Examination

Visual examination is often thought of as being associated only with dimensional inspection; however, this is far from the case and the notion should be discouraged. The machinist should be doing a visual examination of the part, or of a representative number of components at various times during the shift. Not infrequently, an alert machine operator will notice that the chips are breaking off in an unusual and repetitive manner that might indicate a crack. Porosity or a pocket of trapped slag remaining from ingot piping may be uncovered. The machining behavior itself compared with past experience may indicate some significant difference. Unexpected warping or distortion might flag a problem that originated in forging or heat treatment. Sharp in process visual examination then will often lead to the discovery of features that if not recognized could lead to wasted time, money, and resources later in the process. This kind of early warning can get lost if the work ethic is poor, or perhaps from operator greed in not wanting to run the risk of losing some production premium, or as unfortunately happens because of ill informed supervision.

The use of stereo microscopes is well recognized in some micro assembly and inspection operations, particularly in the electronics industry; however, the use of these instruments tends to be restricted to the laboratory when dealing with forgings. They are certainly most useful in examining tension and impact test fractures, for example. A class of stereo low power microscope that is used surprisingly little in the metal manufacturing industries, however, is the long working distance medical operating microscope [1]. These can be equipped with objectives that permit working distances of 2 ft (600 mm) or more and can be used in conjunction with video cameras. Designed for operating room use, the erect image and low level of eyestrain make these instruments ideal for shop or field inspection at least for special situations. As an example, a situation arose in the 1960s involving two small high-pressure steam turbines used to drive generators in a chemical plant. The pass out or exhaust steam was used for process heating. The turbines were in a fairly new installation that was covered by loss of use insurance. A blade failure in one unit shut part of the plant down and necessitated the rotor being returned to the manufacturer for repairs, including replacement of the stainless steel blades. Investigation revealed that two or three blades in one stage had failed by fatigue at the blade root radius where a sharp edge had been left. The probability of similar failures in the second turbine was considered to be high, and an inspection was ordered on site. The question was how to do it. Magnetic particle examination was eliminated since the blades were nonmagnetic. Liquid penetrant examination would be difficult and messy because of the small size of the blades and the failure proximity to the blade root attachment to the rotor. The rotor would also have to be removed from the steam chest, and facilities for doing this were very limited. Because of the small blade size, the austenitic material, technique difficulties, and lack of standards, ultrasonic examination was going to be difficult as well. The decision was taken to examine the rotor blades row by row using an operating microscope. The top half of the steam chest was removed, and the microscope set up by clamping the bench stand to a firm support that facilitated focusing on the blade root area at a working distance of about 20 in. (500 mm). The rotor was turned manually and three or four blade root areas could be examined at each step. The microscope was moved as necessary along the length of the rotor to enable all of the blade stages to be examined. Cracks were found in this way in three blade roots in the same stage as the failures in the first turbine. One successful operation of this type can more than pay for the equipment outright. The general setup used for another rotor is shown in Fig. 11.1.

Magnetic Particle Examination

Surface examination by the magnetic particle examination method is widely practiced both during forging manufacture and in the field. It is capable of revealing various surface, or when direct current magnetization is used, near surface indications. With a magnetic field applied to a ferromagnetic forging, magnetic flux leakage at a discontinuity will attract fine magnetic particles and make it readily visible. For complete coverage, the magnetic field must be applied first in one direction and then, after inspection, applied again at right angles, that is once longitudinally and then in a transverse or circumferential direction. The magnetic field can be generated by passing a high amperage current through the piece itself, by the use of a central conductor, by wrapping cable coils round the part or by the use of an electromagnetic yoke. Although not used for routine magnetic particle examinations strong permanent magnets are useful sources of magnetic flux, particularly for difficult field situations. Permanent magnets, for example, were used for many years in the field inspection of riveted boilers for caustic (stress corrosion) cracking at rivet holes, before the introduction of ultrasonic examination made rivet removal unnecessary.

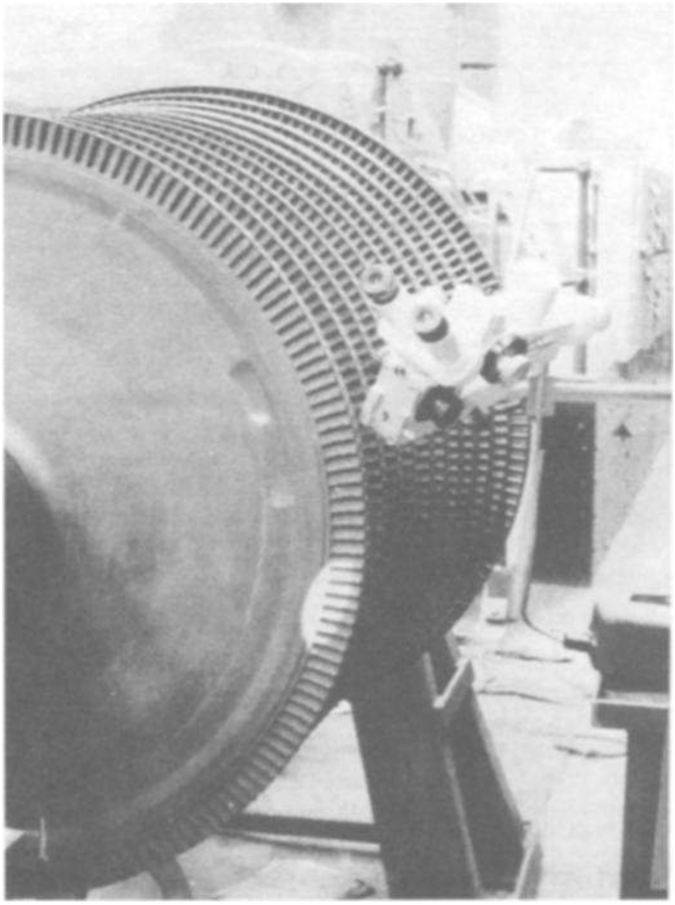

Fig. 11.1—Use of a long working distance operating microscope in the nondestructive examination of a steam turbine rotor.

Magnetic fields derived from direct current (full or half wave rectified ac) provide the ability to detect near surface discontinuities and is most useful in that respect. However, demagnetization afterwards is sometimes difficult. As an example of this, some forged cylinders were made for a nuclear pressure vessel evaluation study. The forgings were made to Specification SA-508 Class 2 and were about 36 in. (915 mm) in diameter with a length of about 6 ft (1.8 m) and a wall thickness of about 6 in. (150 mm). Magnetic particle examination of the finished forgings was completed to the specification requirements, using Method SA-275/SA-275M Magnetic Particle Examination of Steel Forgings, and this was followed by demagnetization. On arrival at the fabricator's facilities the first order of business was to slit the cylinders longitudinally to prepare for a longitudinal weld seam that was required for the study. On completion of the longitudinal cut the residual magnetic field across the gap was strong enough to hold a large wrench in place, making welding of the longitudinal seam impossible. The forgings had to be returned for further demagnetization, using considerably higher currents than had been used in the original magnetic particle examination.

The use of an a-c power source provides adequate surface magnetization capabilities, but the depth of subsurface discontinuity detection is greatly reduced when compared to d-c magnetization. However, for certain applications, such as crankshafts, where the risk of severe service damage due to the pick up of magnetic particles from the lubricating oil is very high, a-c magnetization is preferred because of the ease of demagnetizing after the magnetic particle examination.

Other major ASTM standards for magnetic particle examination are E 709, Guide for Magnetic Particle Examination, and E 1444, Practice for Magnetic Particle Examination. While these standards deal with the subject admirably, there are special shortcomings with regard to large forgings. This is because when dealing with large components the calculated current required for magnetizing can become very high, in frequent situations a large 20 000 ampere machine would not be big enough, and worse, spurious indications attributable to forging grain flow would appear. Test Method A 275/A 275M was written because of these problems. This test method is a mandatory part of many steel forging material specifications such as A 508/A 508M. It should be noted that Method A 275/A 275M provides only the test method, not acceptance criteria, since these lie in the province of the product specification. Another more recent ASTM test method for magnetic particle examination is A 966/A 966M, Magnetic Particle Examination of Steel Forgings using Alternating Current. This specification parallels Test Method A 275/A 275M, and was written to provide a test method for the examination of components such as large crankshafts where certainty of full demagnetization is imperative. A companion specification, A 986/A 986M, Magnetic Particle Examination of Continuous Grain Flow Crankshaft Forgings, provides for acceptance criteria.

There are variations in magnetic particle examination methods that should be addressed. The most sensitive is the wet fluorescent method. This as the name suggests uses fluorescent particles suspended in a carrier liquid, and the part is examined under ultraviolet (black) light. The indications fluoresce as shown in Figs. 11.2 and 11.3, and even very small ones can be readily seen. This method works extremely well with very finely finished surfaces, such as the journal surfaces, fillets, and oil hole radii in large continuous grain flow crankshafts. If the machined surface finish is not smooth, retained particles in suspension can make interpretation difficult. Although makeshift viewing areas can be established using tarpaulins, permanent inspection booths with removable covers make for a better environment for the test.

After the wet fluorescent method, the wet method using nonfluorescing particles in suspension is the next lower level of test sensitivity, and depending on the application and the minimum allowed flaw size is fully adequate for most situations where one is looking for crack-like indications, porosity, large inclusions, or weld defects. Linear indications shorter than 0.125 in. (3 mm) on smooth surfaces can be detected readily by this method. This is probably the most widely used of the magnetic particle examination methods. The use of dry powder, especially on rough or warm surfaces, is useful for the larger indications, such as quench cracks or hot cracking in welds. It is also a very useful system when following the course of an indication during its removal by grinding, since there is no fluid to fill the cavity and hinder the examination.

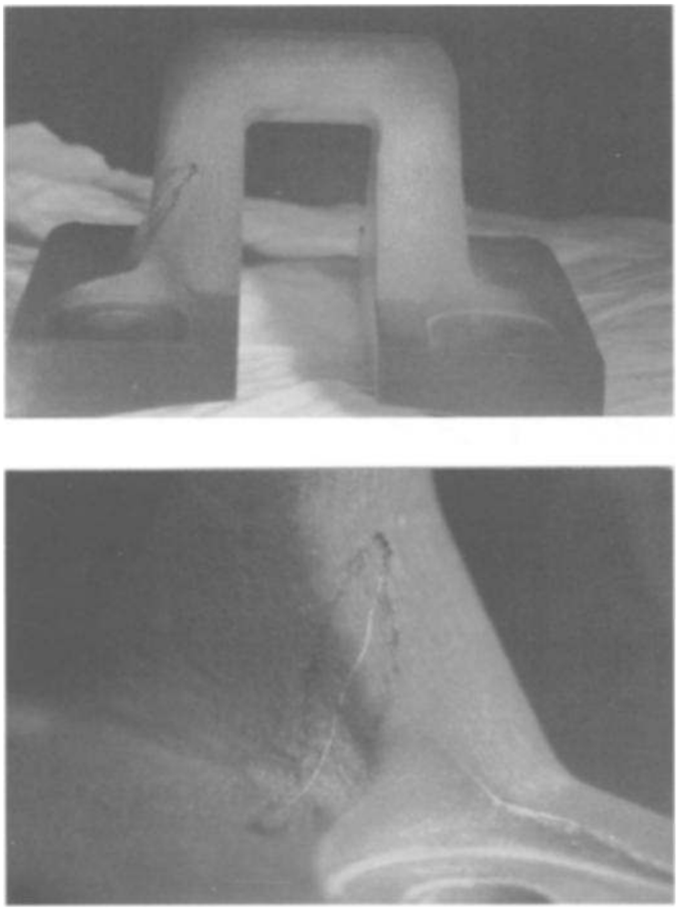

Fig. 11.2—A fluorescent magnetic particle indication photographed under "black" light. The closed alloy steel die forging was heat treated and the as forged surface was cleaned to remove scale.

The use of the residual magnetism method, where the particles are applied after the current has ceased to flow, is little used and is not generally recommended.

Mention must be made of magnetizing localized areas by the use of hand held powered prods. Used particularly in the field, they are associated with portable kits with a lower current capability than would be found with the larger fixed shop equipment. The prods are pushed onto the test surface and are held in place while the current flows through the prods into the part. Test Method A 275/A 275M specifies the prod spacing on the surface—generally about 6 in. (150 mm) is used. The magnetic particles are applied while current is flowing, and after examination the same surface is magnetized again at right angles to the first shot. The prods are then moved to another area, allowing for overlap, and the procedure repeated. Dry magnetic powder (available in several colors) is most often used in this method, but a wet suspension can be used also. The dry powder tends to build up around the pole pieces so that the overlap must cover these areas. For large areas, the surface should be laid out in a grid pattern beforehand.

Arc strikes between the prods and the work surface are a distinct and serious risk and must be minimized, and preferably avoided. Various prod designs are available to help reduce tendencies for arc strikes, since these are a source of cracks and grain boundary copper penetration. A similar situation must be guarded against when using clamps to connect power cables to the forging for direct magnetization. Braided copper fabric is sometimes used between the clamp and the forging to minimize the possibility of burning. Figure 11.4 illustrates severe arc burns with copper deposits.

Recording of indications is possible by using dry powder and picking up the indication trace with transparent adhesive tape and transferring it to a piece of white paper. An example of this technique used to monitor a lamellar indication located near the manhole of a large water-tube boiler drum over an interval of two years is shown in Fig. 11.5. The test methods describe some of these options.

Liquid Penetrant Examination

The liquid penetrant procedures in use today are covered by ASTM E 165, Practice for Liquid Penetrant Examination. The origins of this test method are not known for certain, but during World War II a practice known as Oil and Chalk testing was used to examine magnesium alloy aero engine crankcases and gear covers for porosity and cracking. The part was immersed in a warm light mineral oil for a defined period, then drained and wiped dry. The surfaces were then sprayed with a dry chalk powder, and after a few minutes examined for oil stains that indicated the location of defects that were open to the surface. The current methods use a red dyed low viscosity vehicle with a low surface tension that is capable of penetrating into pores and fine tight cracks at room temperature. Time is allowed for the liquid to penetrate, and then the surface is wiped clean and a fine white chalk like developer is sprayed on the surface. After the required development time, the surface is examined for telltale red stains. As would be expected cracks produce a fine red line, and pores show as red dots. However, a closely pitched

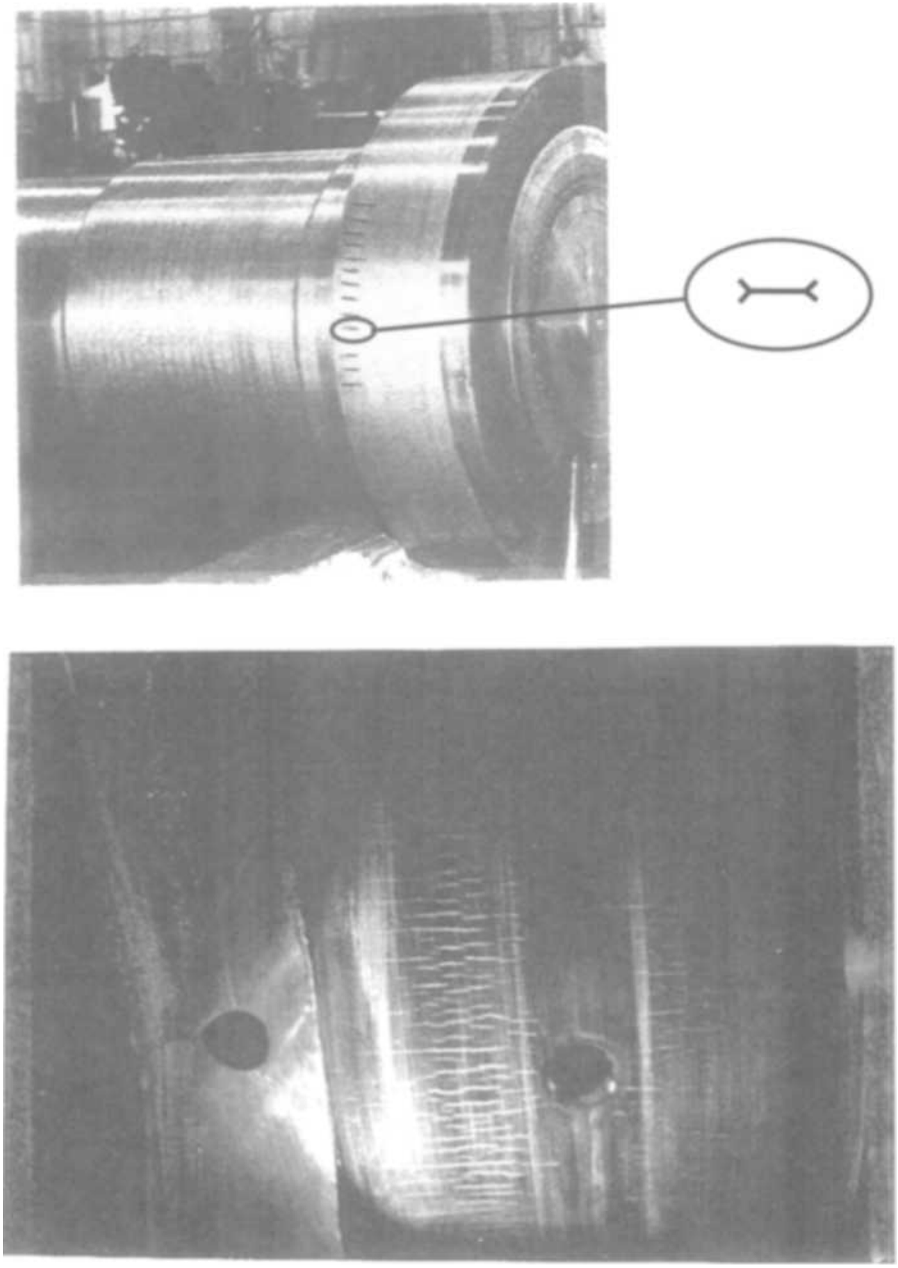

Fig. 11.3—Sketch of a typical grinding crack pattern. The shallow parallel cracks are usually very short and oriented at right angles to the direction of the grinding wheel. When viewed under some magnification the cracks have forked ends making them potent stress concentration points for propagation by fatigue. The similarity of the cracking pattern on a crankshaft bearing surface as a result of bearing seizure (lower picture) is evident.

series of red spots frequently marks the presence of a very fine tight crack. The penetrant indications become more diffuse over time as more dye seeps from the indication. As with most surface examinations, surface finish is important, and a coarse machined or shot blasted surface tends to leave a strong pink colored background that can interfere with the final examination.

As with magnetic particle examination, a fluorescent dye is available and the examination is done on the developed surface using an ultraviolet light source. As with the magnetic particle examination, the fluorescent system enhances the inspection sensitivity.

The liquid penetrant method, while mainly used on nonmagnetic materials such as the austenitic stainless steels and nonferrous materials, is also used quite widely on ferromagnetic materials where the preferred magnetic particle equipment is not available.

Volumetric Examination

Although radiography is widely used in the examination of castings, both ferrous and nonferrous, and weldments, it is little used for steel forgings. This is not simply because of the size and cost of the equipment involved, the time element

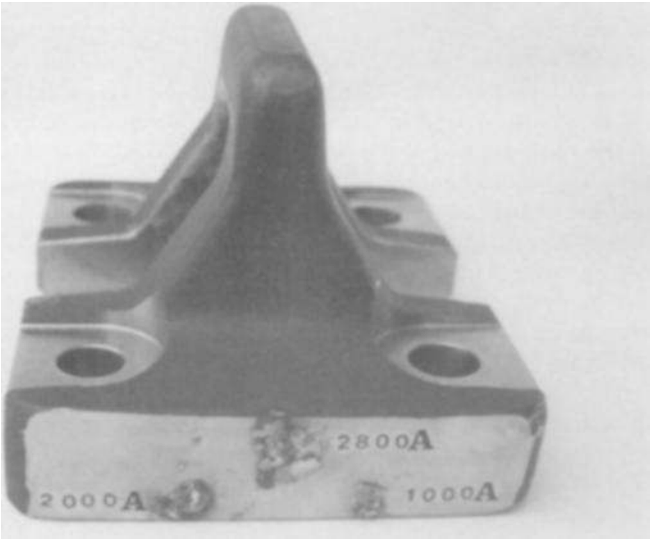

Fig. 11.4—Effect of increasing magnetizing current on copper deposits from contact prods on an alloy steel forging.

to do the examination, and the need for personnel protection, but because of insufficient sensitivity in thick sections. Ultrasonic Examination has been found to be ideal for volumetric examination of steel components, and two major ASTM test methods have been written to detail the equipment and procedures that are recommended for steel forgings. The first and more important of these is Practice A, 388/A 388M, Standard Practice for the Ultrasonic Examination of Heavy Steel Forgings. The second forgings standard is A 745/A 745M, Practice for Ultrasonic Examination of Austenitic Steel Forgings. The two practices are necessary because of the major differences in the propagation of sound waves in ferritic and austenitic forged materials, particularly attributable to the coarse grain size generally found in large austenitic steel forgings.

The ultrasonic examination equipment has increased in robustness, and decreased steadily in size over the years, and it is not uncommon, particularly for interim examinations, for the ultrasonic examination equipment to be carried to the forging, rather than the other way around. However, from a scheduling point of view, and because the magnetic particle examination transformer/rectifiers are large and static, the final nondestructive examinations are usually done in a central location.

Forging complexity, apart from size, sometimes dictates that ultrasonic examination be done at interim stages of manufacture, if in the final state a full 100 % volumetric examination is not possible. A general specification requirement is that the ultrasonic examination be done after completion of the quality heat treatment. For large and complex components, such as the main reactor vessel nozzles in a pressurized water reactor (PWR) unit, it is often the case that the forging is contour machined to follow the final shape prior to heat treatment so that important highly stressed final surfaces are as close as possible to the quench medium, and so can be expected to enjoy maximum toughness. In this format, a full volumetric ultrasonic examination

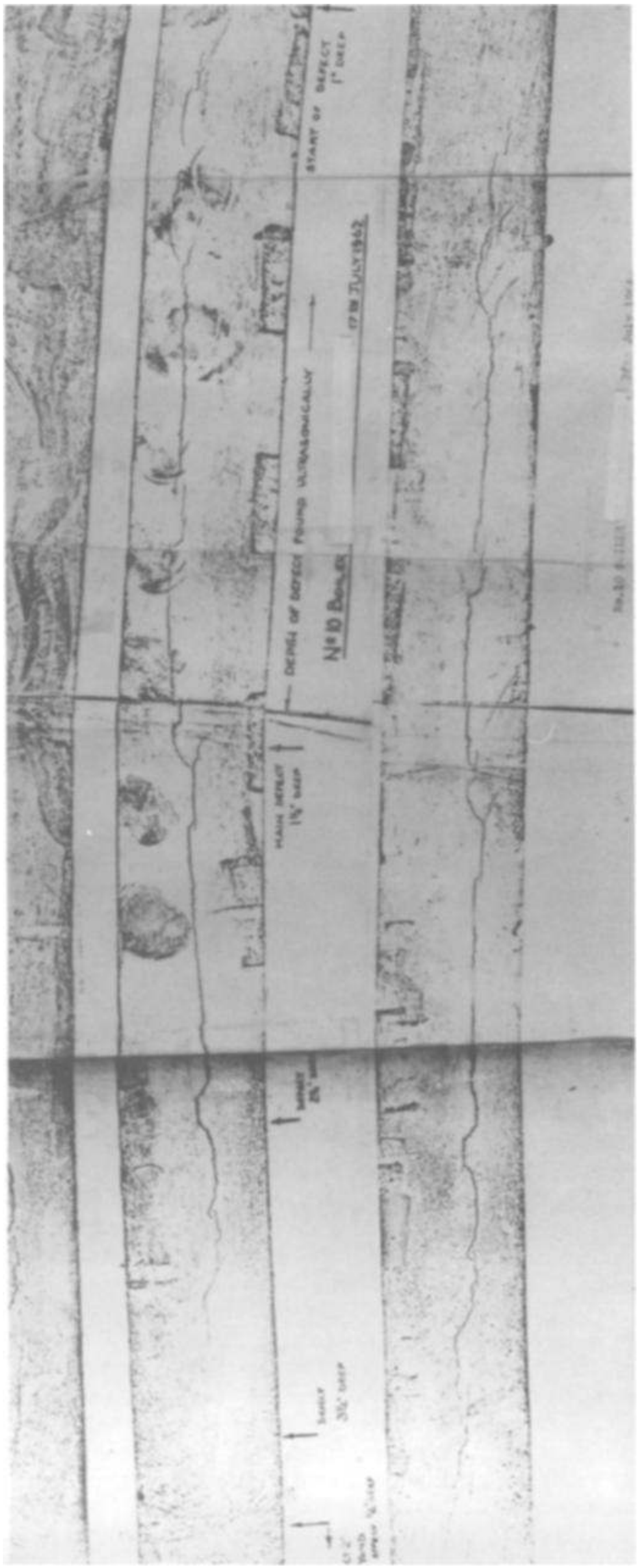

Fig. 11.5—Magnetic particle indications lifted on site from the manhole of a fabricated boiler drum by means of transparent adhesive tape and transfer to a white card. The area was scanned also by ultrasonic examination. The lamellar type defect was examined two years later and comparison of the two results showed little if any change.

after heat treatment may not be possible so that an intermediate examination must be done prior to the contour machining and heat treatment. Following heat treatment, the ultrasonic examination is repeated to the maximum possible extent. As an adjunct to this, if 100 % volumetric coverage *is possible* after heat treatment, but not in the final machined shape, then the part must be given the ultrasonic examination before the final shape is generated.

Surface finish is important for ultrasonic examination and is dealt with in the applicable practice.

Geometric features, such as diameter changes in shafts, produce natural reflectors during ultrasonic examination and must be recognized, especially if they are hidden in a bore. The geometry aspect becomes very important when working on a complicated shape such as a crankshaft.

Some types of defect have characteristic ultrasonic responses, and recognition of these can assist greatly in the interpretation of what is causing the indication. For example, when performing a radially oriented scan through a solid cylindrical forging, such as a roll, a return echo from the opposite side is expected and, indeed, is part of the setting up process for the examination. This is known as the back reflection. If the back reflection should diminish or disappear during the scan, this indicates that the sound beam is being absorbed or scattered on its way through the section. This loss of back reflection may be accompanied by another reflection from some point within the section and could be caused by the presence of voids, perhaps a remnant of ingot piping, or a large group of inclusions. The behavior of the sound beam at different locations round the circumference and the appearance or disappearance of intermediate peaks in the CRT display all help to build up a picture of what the discontinuity is. Loss of back reflection is a significant result of the examination, so much so that some acceptance criteria is based on a 50 % or greater loss of back reflection (reflection peak reduced by half) occurring together with an intermediate indication spaced between the initial pulse and the back reflection peak. In austenitic stainless steels, this situation can be caused simply by a significant change in grain size, with no actual defect present. As an example [2], a long cylindrical forging to SA-336 Grade F304 intended for use in a reactor containment penetration application in a nuclear power station was straightened at the forging press by pushing on it between offset dies. The temperature of the piece at that time was below the recrystallization temperature. After machining and boring, the part was solution annealed by water quenching from the solution annealing temperature. An area of the forging about 6 in. square (150 × 150 mm) showed a large loss in back reflection during the radial compression wave scan, and some short reflections were noted near the OD surface. Metallographic examination showed an area of very coarse grain size that apparently was formed when the lightly warm worked area formed during the straightening operation recrystallized to give significant grain growth during solution annealing. The part was not accepted, and subsequent destructive examination, while confirming the presence of the coarse grains failed to show any defects.

Frequency of the search units is important. For most applications in ferritic steels, a 2.25-MHz search unit frequency is adequate. For coarse-grained materials, dropping the frequency to 1 MHz may be necessary and this is often the case when scanning austenitic stainless steel forgings. Increasing the frequency to 5 MHz and reducing the transducer size to 0.5 in. (12 mm) is useful in scanning small areas at high sensitivity. Generally, ferritic steels respond better to ultrasonic examination after heat treatment because of the more refined and uniform structure, and most specifications require that the examination be done after the quality heat treatment. In some special situations a complete volumetric scan at the required sensitivity may have to be done before contouring the forging for heat treatment. In such cases a preliminary normalizing treatment should be considered to refine the grain before the examination. This normalizing, of course, would not need to be repeated for the final cycle. The final ultrasonic examination is then done to the maximum possible extent after quality heat treatment.

Having found an indication, there remains the problem of assessing its size, a necessary precursor to determining its acceptability. Earlier, it was mentioned that a given percentage loss in back reflection, accompanied by an indication is used as an acceptance criterion for some product specifications. A more meaningful system uses a distance/amplitude correction curve to assess an indication according to its distance from the transducer. A group of test blocks of the same material and heat treatment condition, but of differing lengths, is used to construct the curve, each block having a flat bottomed hole of specified diameter drilled in one end to give a series of test distances. The readings from these blocks establish points through which the curve can be drawn and establish an acceptance line for the forging. The test hole diameter establishes the sensitivity of the test and may be specified in the product specification or in the purchase order.

For the shear wave examination, notches located in the outside and inside diameters of the part are used for calibration purposes. These are oriented in the longitudinal direction for the circumferential scan, and in the circumferential direction for the axial scan of the forging wall. There are geometric limitations on the circumferential shear wave examination of hollow cylindrical parts that are tied to length, wall thickness, and diameter. The length of the ring or cylinder must exceed 2 in. (50 mm), and the ratio of the outside to inside diameters must not exceed 2.0:1. The sensitivity of the shear wave scan is determined by the depth of the calibration notches. This is usually expressed as a percentage of the wall thickness, and Practice A 388/A 388M requires a maximum depth of 3 % or 0.25 in. (6 mm). Practice A 745/A 745M for austenitic stainless steel forgings offers two shear wave quality levels, QA-1 at 3 % of the wall thickness and QA-2 at the lesser of a maximum of 5 % wall thickness or 0.75 in. (19 mm).

The ultrasonic examination practices will be discussed further in the discussion of Practices A 338/A 388M and A 745/A 745M.

Coupling between the probe and the workpiece is an essential part of ultrasonic examinations. This may be in the form of water based gels or mineral oils, engine lubricating oil being commonly used for this purpose. Where further machining or heat treatment follows the examination, the water-based materials are often preferred to reduce smoke, while at the final stage oil reduces surface corrosion.

In-Service Inspection

While magnetic particle, liquid penetrant, and ultrasonic examinations are done routinely during forging manufacture for quality and certification purposes, these test methods and practices are also used extensively to monitor forgings in the field. Such examinations are aided immensely by having the detailed original reports available to the inspectors, particularly if acceptable indications have been recorded and can be looked at afresh after service. The importance of prior inspection reports cannot be over emphasized, particularly the retention of detailed reports that may not be required for the final certification, where simply an expression of complying with some product specification requirements may be all that is required. It is not suggested that such detailed reports be provided to the purchaser, unless there is some agreement to do so, since too much information beyond that required by the specification and the purchase order can frequently cause a great deal of confusion and heartache. This subject will be discussed further in Chapter 20; however, it is important to be aware of the level of the original examinations. For example, the calibrations used in the original ultrasonic examinations should be known, so that both the original and the in-service results can be compared directly.

References

[1] Nisbett, E., "Metallurgical Influences on Plant Inspection," ASME International Pressure Vessel and Piping Division, Paper 70-PVP-5, Denver, CO, September 1970.

[2] Nisbett, E., "Metallographic Control of Heat Treatment," *Metallography as a Quality Control Tool*, French/McCall, Eds., Plenum Press, July 1979.

12

Surface Treatment

IN MANY INDUSTRIAL APPLICATIONS THERE ARE advantages to be had by surface treatment of forgings. The most important of these are:

- Improve Wear Resistance
- Improve Fatigue Strength
- Reduce Galling

The most common methods of surface treatment include:

- Direct Hardening by Heat Treatment
- Nitriding
- Carburizing
- Salt Bath Treatments
- Hardening by Cold Working
- Proprietary Chemical/Salt Bath Treatments

The choice of surface treatment relates to the type of steel involved, the required surface effect, equipment availability, and the design application. The component designer usually specifies the surface treatment requirement, or may simply specify the end properties and leave the method of obtaining them to the forging supplier. The most satisfactory and useful arrangement is to decide on these details with the forging supplier before the final design is fixed.

Direct Hardening

The direct hardening methods are probably the most common and span a wide range in both size and application. Their use depends on the base material being capable of yielding high hardness values, and therefore, the carbon content is most important. The steels used then are typically in the medium carbon range from 0.4 to 0.65 %, and may or may not be alloyed, depending on the requirement for core tensile strength and forging size. The process consists of austenitizing a surface layer, followed by rapid cooling to form a martensitic skin. The hardened surface is usually lightly tempered, perhaps between 200 and 500°F (110 and 260°C) before finish grinding to size. The depth of hardening can be varied according to the heating system but would typically have a maximum depth of about 0.375 in. (10 mm), although much greater depths are obtained in certain special applications such as rolls for rolling mills.

When originally developed the heating system used gas burners, and went by the name Flame Hardening. A setup for vertical flame hardening of a roll surface is shown in Fig. 12.1. The advent of electrical induction heating equipment permitted faster heating even over quite complex shapes by the use of special coils, and importantly automation. Known as Induction Hardening, such systems are widely used in the automotive industry for a wide range of components and permit the use of relatively inexpensive materials. More generalized induction hardening equipment for very varied applications, such as the surface hardening of bearing surfaces of shafting, and producing wear resisting surfaces for the corrugating rolls used to produce corrugated paper board, permits the wider use of induction hardening for smaller component quantities. Induction hardening is widely used in automotive and truck crankshaft production. The main purpose is to reduce bearing journal wear and so extend crankshaft life, but if the crankshaft journal fillets are hardened also, then a significant increase in fatigue strength is obtained. This can avoid the need for more expensive alloy steels, or can enable the engine power output to be increased without a crankshaft design change. Increased risk of distortion as a result of fillet hardening is a disadvantage that has to be addressed, however. An example of induction hardening diesel locomotive crankshafts is shown in Fig. 12.4.

Great care must be taken in the grinding of induction-hardened surfaces to avoid the formation of grinding cracks that generally are devastating to the life of the component unless removed. This problem was discussed in the chapter on machining, and although isolated cracks can occur, frequently several parallel cracks follow the track of the grinding wheel as shown in Fig. 11.3.

Although an induction hardened surface can be rehardened if there was some problem with the initial treatment, some precautions must be taken to reduce the risk of cracking on repeating the procedure. The hardened surface should be tempered back before attempting to harden the part again. As in induction heating for forging, if a part is to be reinduction hardened, then its temperature should be allowed to cool to ambient, since residual heat in the part will increase the surface temperature during the austenitizing stage (at the original power setting) and increase the risk of cracking during quenching. Light tempering after hardening is always advisable, since delayed cracking of untempered martensite is always a risk, particularly when dealing with alloy steels. Hydrogen in the base material is a possible source of this problem.

Although there will be a degree of self-quenching when the heating of the surface ceases as the coil moves on, this being caused by rapid conduction of heat from the surface into the core of the part, external quenching is almost always applied. Although water can be used for this, probably the most common quenchant is a polymer/water emulsion. These cool more slowly than water, but they do not cause corrosion of the machine equipment, and reduce cracking tendencies while still giving adequate surface hardness.

Maintaining machine settings in terms of power supply, coil travel speed and quenching coil position are essential for obtaining repeatable results, especially since determining the case depth and hardness pattern must be done by destructive testing. This can be quite expensive and time-consuming when one considers complex forgings. It should

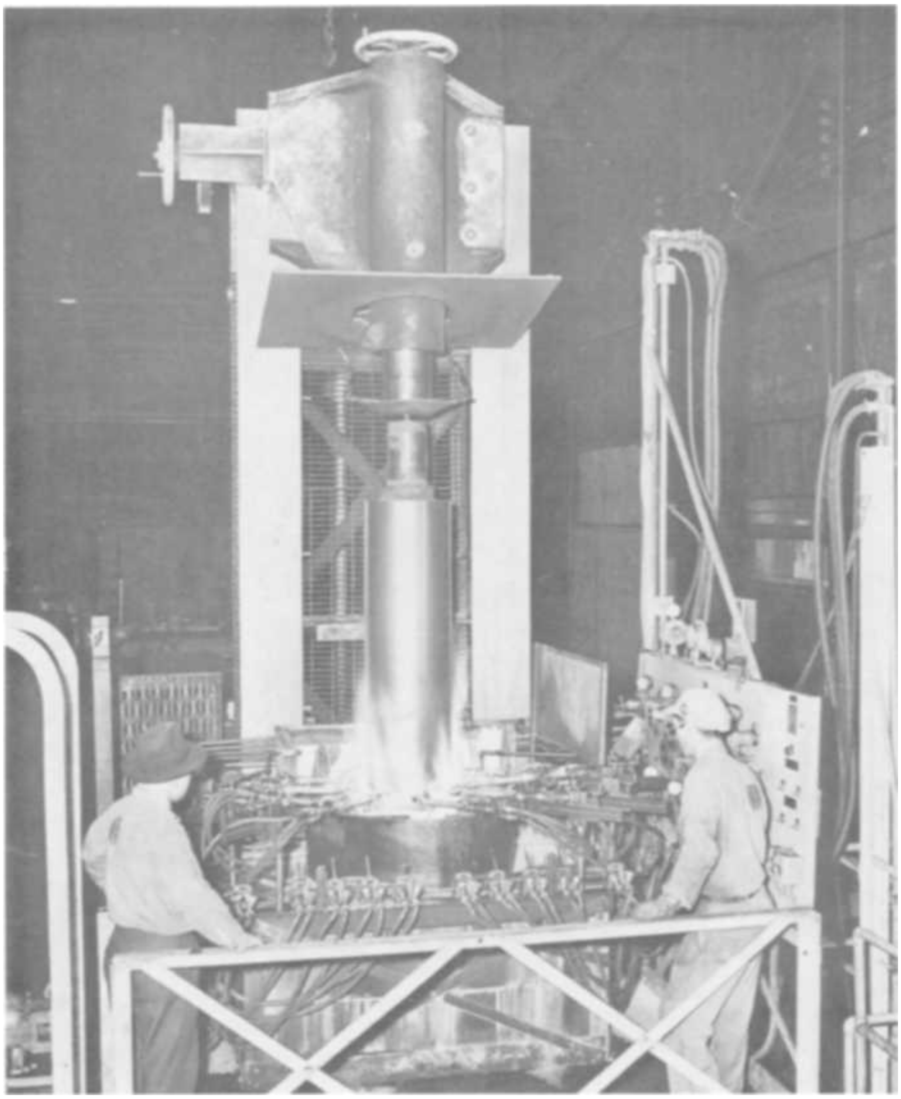

Fig. 12.1—A vertical flame hardening machine in the process of surface hardening a pressure roll to ASTM Specification A 649/A 649M.

be remembered that although the time of exposure to high temperature is short, a little decarburizing does take place, so that the immediate surface hardness will be lower than the area directly underneath. Since portable hardness testing is often used as a quick quality guide, the test spot should be lightly ground to improve the surface finish and remove the decarburized zone.

The depth of hardened case can be determined metallographically by looking for the end of the transformed surface zone in a cross section, but a more practical method is to run a hardness traverse through the case and into the base material. The hardness will remain steady in the outer parts of the case, and will then decline towards the base hardness. The sharpness of this drop is of interest to some designers, and can be controlled by adjustment of the induction hardening and quenching parameters. At the base of the case, a shallow area softer than the original base hardness should be found, depending on the original heat treatment. This results from localized over tempering during the surface austenitizing stage. The depth of the case would be reported as the depth at which the case hardness falls to some predetermined value, perhaps two Rockwell C scale points higher than the maximum base hardness.

Nitriding

The two principal methods of nitriding steel today are by Gas Nitriding and Ion Nitriding [1,2]. Nitriding is the introduction of nascent nitrogen by diffusion into the steel surface and the formation of nitrides typically of iron, chromium, and aluminum. Whereas induction hardening is done by austenitizing the surface to be hardened, nitriding is typically done in a furnace operating at about 925/975°F (495/525°C) for single stage nitriding, or 925/1050°F (495/565°C) for the double stage gas nitriding process. Nitriding also differs significantly from induction hardening in terms of case depth, the maximum nitrided case depth being of the order of 0.20 in. (5 mm). Surfaces, therefore, are usually very close to the finished diameter when nitrided, whereas induction hardened surfaces almost invariably are hardened with excess stock present and are finish ground to size afterwards. Since it is a diffusion controlled process nitriding is quite slow, and for the gas process in particular can take several days from loading to unloading the furnace.

A feature of nitriding is the formation, or at least the tendency to form, a friable iron nitride surface film called White Layer. This film is troublesome in some applications if it should become detached, and has to be removed after nitriding. This can be done readily by polishing or by chemical means.

Gas Nitriding

Although some nitriding processes are available utilizing salt baths, the original widely used process was gas nitriding using anhydrous ammonia as the nitrogen source and carrying out the operation in an electrically heated retort or furnace. The furnace is provided with a circulating fan to distribute the ammonia/nitrogen. After loading, air must be purged from the furnace before starting to heat the charge. This is necessary to prevent oxidation of the component surfaces. Nitrogen rather than ammonia is increasingly used for this initial purging operation. Depending on the degree of ammonia dissociation required, the incoming ammonia may be passed over a catalyst to increase nascent nitrogen supply. For the single stage nitriding process a dissociation of 15/30 % is used and this can be obtained simply by contact with the steel component at the nitriding temperature. The second stage of the double stage or Floe process requires 80/85 % ammonia dissociation and for this the ammonia is passed over a catalyst before entering the furnace. Since the dissociation of ammonia produces a significant quantity of hydrogen, care has to be taken to exclude air particularly during the cool down period at the end of the cycle. Purging with nitrogen during this cooling stage is used to economize on the use of ammonia and to lessen ammonia emissions to the atmosphere. This enables the furnace to be opened above 300°F (150°C) without the otherwise attendant risk of explosion. A nitriding load is shown in Fig. 12.2.

The single stage nitriding process will produce the required case depth and hardness, but is accompanied by a surface iron nitride compound about 0.002 in. (0.05 mm) in depth called White Layer or Compound Layer. White layer is friable and is often considered to be objectionable in service, because of damage potential, for example, to white metal bearings, when it breaks away from the nitrided surface. The double stage nitriding process was patented many years ago by Dr. Carl Floe and is often known as the Floe Process. This differs from the single stage procedure by increasing the ammonia dissociation in the second stage to about 80 % and increasing the temperature from about 950°F (510°C) for the first stage to 1000°F (540°C) for the longer second stage. The major advantage of the Floe Process lies in the reduction of the white layer thickness to less than 0.001 in. (0.025 mm), an amount easily removed by final polishing of the surface.

Being a diffusion process, nitriding unlike induction hardening is slow, so that from loading to unloading the nitriding furnace five or six days might elapse, depending on the length of the actual nitriding stage, which might range from 65 to 80 h. As has been mentioned specialized furnace equipment as well as ammonia and nitrogen sources have to be provided. As in all surface hardening procedures, staff training and documented working instructions are vital both from the points of view of safety and consistency.

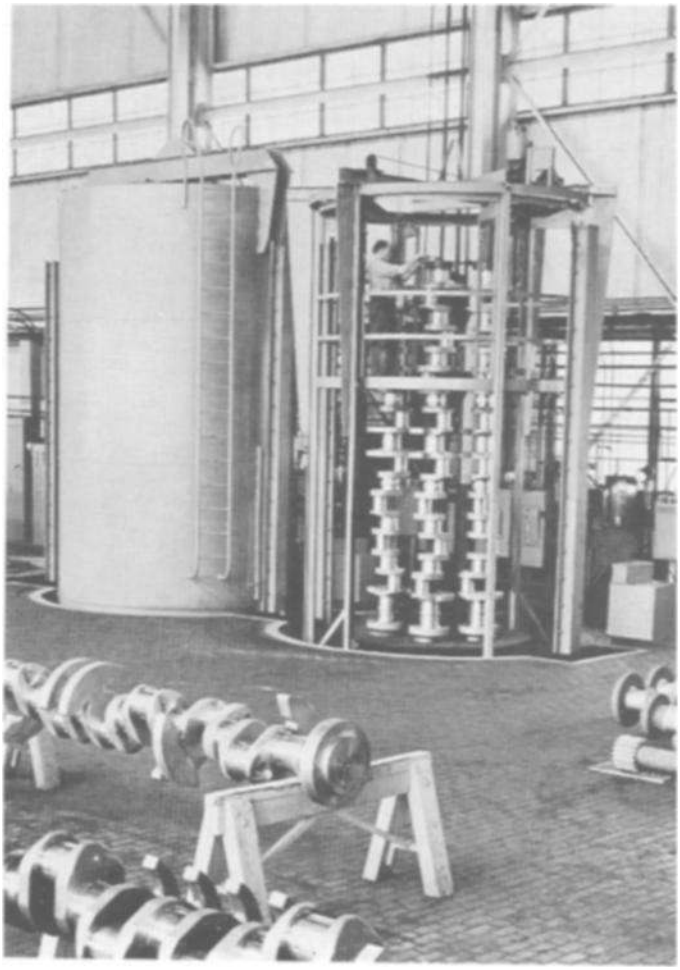

Fig. 12.2—A large vertical gas nitriding furnace being loaded with crankshafts. The furnace bell sits nearby ready to be lifted over the load. In the foreground, crankshafts are being prepared for nitriding by painting areas that are not required to be hardened. (Courtesy Ellwood National Crankshaft Company)

The literature reports nitride case depths from as little as 0.010 in. (0.25 mm) to as much as 0.040 in. (1.0 mm) in alloy steel. The author's experience is with case depths of 0.025 in. (0.6 mm) after double stage nitriding. The nitrided case depth requirement is frequently expressed as a minimum hardness at a given depth from the surface, such as 44HRC at 0.015 in. (0.38 mm). The actual minimum hardness would depend on the material being nitrided, of course.

In general, for nitriding the maximum case hardness increases with increasing core hardness, but the steel composition has the major influence on the case hardness. Aluminum is a strong nitride former and the hardest nitrided cases (of the order of 67HRC) are obtained with high aluminum steels such as the Nitralloy types that contain about 1.0 % aluminum. Specification A 355 Steel Bars, Alloy, for Nitriding includes one such steel as Class C. The high aluminum content of the Nitralloy steels renders them prone to having significant amounts of alumina type inclusions, a distinct disadvantage for some applications, but the advent of vacuum metallurgical procedures has helped greatly in mitigating this disadvantage. Probably the chromium molybdenum 4100 series alloy steels are the most commonly used for nitriding, particularly 4130 and 4140, which yield a case hardness of about 50HRC; however, the higher chromium types such as Grade 7 of Specification A 983/A 983M with 2.8/3.3 % chromium give an increased case hardness approaching 60HRC. Chromium bearing tool steels such as H11 respond well to nitriding. Nickel tends to inhibit nitriding, so that the 4340 grade does not respond as well as 4140 for the same nitriding cycle.

Like carburizing and induction hardening, nitriding does more than increase the surface hardness. The nitrided case imparts a compressive residual stress to the surface that is very beneficial under fatigue loading conditions. Often nitriding is specified to improve fatigue strength with wear resistance as a secondary benefit. It should be remembered, however, that as with the other surface hardening techniques, a residual tensile stress is present at the base of the case, and that this will be exposed if the case is locally removed.

It is frequently unnecessary and unwise to nitride the whole component, so that selective blocking of the nitriding process is required. This can be done using tin based paints or by tin, bronze, or copper plating. These days painting avoids the many environmental problems surrounding plating, and of course, the areas to be nitrided would need to be protected from plating, an added expense. The tin paints work well on machined surfaces if care is taken in cleaning them beforehand, and it is essential that the paint is kept well stirred, preferably continuously so. On scale free, as forged surfaces it should be recognized that painting does not consistently protect the surface, possibly because of the difficulty of maintaining the required paint thickness. A word of caution is in order here. After painting and during drying—certainly before loading into the furnace—the component should be carefully examined for paint spots or runs on the surfaces to be nitrided, since these will effectively prevent the underlying surface from being nitrided. This will produce a non-nitrided island that, depending on its location, could seriously affect the fatigue properties at that location because of the exposed loop of residual tensile stresses. The local loss of hardness under the paint spot may or may not be significant with regard to surface wear.

Since the nitrided component has been taken close to finished size before nitriding, little machining is necessary afterwards. With the double stage nitriding process, finish grinding should not be required, rather polishing and lapping will suffice to obtain the required degree of surface finish, and this will be sufficient for the white layer removal.

A further word of caution is expressed for the handling of large components after nitriding. The nitrided case is hard and brittle so that care must be taken to avoid blows and shocks that apply bending loads to the case since it might crack. Large nitrided crankshafts have been known to snap in two after striking an object while slung from a crane or after falling two or three feet to the floor from a trolley. If handling damage is suspected, the part should be given a magnetic particle examination to ensure that fine cracks, typically in a parallel array as shown in Fig. 12.3, are not present in the nitrided case.

Given that the typical nitriding operation is carried out at temperatures as high as 1000°F (540°C), it will be apparent that the minimum tempering temperature for the material must be appreciably higher than the maximum nitriding temperature to avoid loss in core strength. A temperature differential of at least 50°F (30°C) is considered to be necessary to avoid undue change in the base material properties.

Advances in gas nitriding have permitted closer control on white layer formation [3], and a standard covering the process has been published [4].

Ion Nitriding

The second major nitriding process is ion nitriding, also known as plasma or glow discharge nitriding. This process is done in a chamber under partial vacuum conditions with nitrogen present. The component is set up to be the cathode and the vacuum vessel is the anode. Under low-pressure nitrogen conditions and application of high voltage d-c, a plasma is formed and nitrogen ions bombard the surface of the workpiece. This heats the surface and cleans it by sputtering and provides nitrogen ions for diffusion. A distinct lilac colored glow envelops the part. The operating temperature range for ion nitriding is typically 660–1075°F (350–580°C), with a bias towards the upper third of this range. Energy use is said to be about the same as in gas nitriding, but an essential difference lies in the high degree of control of the case composition. White layer control in ion nitriding is such that this compound layer can be eliminated. Total case depth by ion nitriding is about 60–70 % of that required for gas nitriding.

While stop off paints can be used for selective nitriding, these tend to contaminate the vacuum chamber and the use of close fitting reusable metal shields is preferred for this purpose. This is an added expense, but once provided they are probably quicker to install when compared to the time taken to apply stop off paint. However, frequently the whole part is nitrided, and this may not be desirable in every situation.

The presence of certain holes in the surfaces to be nitrided can cause problems in ion nitriding, due to what is known as hollow cathode or hole discharge, and it is sometimes recommended that these be blocked off by steel plugs. However, in some applications such as crankshafts where fatigue strength is a major factor, it is desirable and even essential that the oil holes be nitrided, since torsional fatigue cracking can start at these locations. This dilemma should be discussed in detail with the nitriding contractor before using the ion nitriding procedure, so that the expectations and potential limitations are understood by those concerned.

Carburizing

Carburizing is the process of enriching a steel surface by the diffusion of carbon, such that subsequent heat treatment will produce a very hard skin. It is generally known as Case Hardening, although this term may now be stretched to apply to other surface hardening procedures. Gas carburizing and pack carburizing are the two main methods in use today, but salt bath carburizing and carbo-nitriding are also of importance.

Historically, pack carburizing came first and consists of heating the component in a closed container packed with a carbonaceous material such as coke, charcoal, or charred leather, together with an energizer such as barium carbonate, such that at the carburizing temperature, carbon monoxide decomposes on the workpiece surface to deposit nascent carbon that diffuses into the steel, as well as carbon

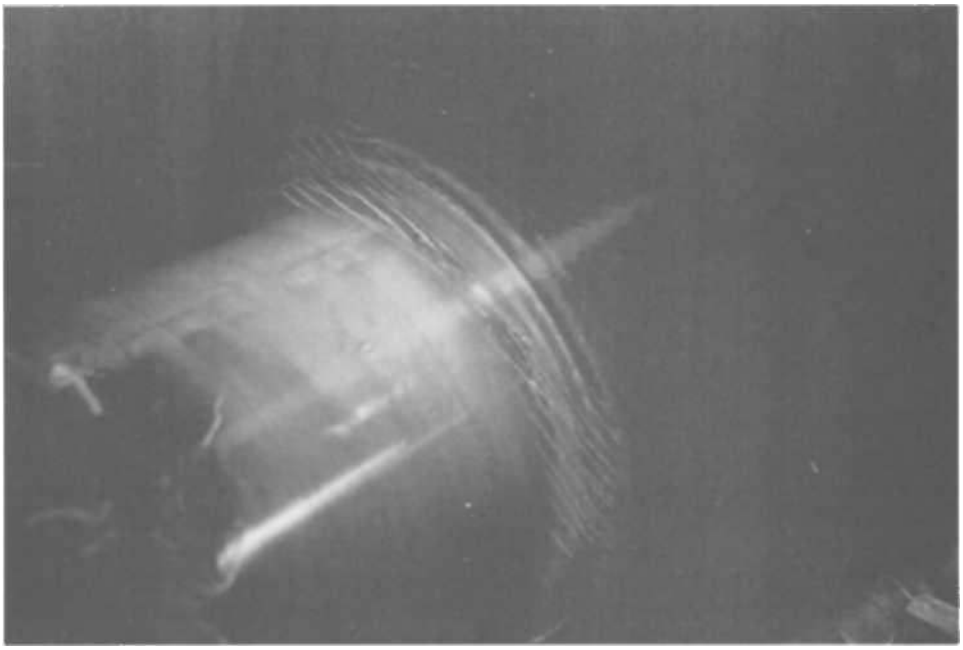

Fig. 12.3—Parallel cracking across the web face and the radius of a nitrided crankshaft. This is indicative of significant bending loads, in this case incurred during an in-service failure. Similar cracking can occur as a result of mechanical damage during mishandling out of the engine.

dioxide that itself reacts with carbon to form more carbon monoxide. Incidentally, this procedure is used in obtaining a Mcquaid–Ehn austenitic grain size sample to ASTM E 112, Test Methods for Determining the Average Grain Size.

Copper plating can be used as a stop off medium to protect surfaces that are not to be carburized, and some paints have been developed for this purpose as well.

For the carburizing stage the container is heated into the austenitizing range, generally to about 1750°F (955°C), although higher temperatures can be used if excessive grain growth can be avoided, and then slowly cooled. Additional machining, if required, would precede the final hardening heat treatment, while the forging is still in a softer condition. Following hardening, the carburized surfaces would require grinding for finishing operations.

In gas carburizing, the cycle is carried out in a controlled atmosphere furnace where a hydrocarbon gas is added to a carrier gas mixture. An advantage of gas carburizing is that the forging could be quenched directly from the carburizing furnace, something that is not normally possible with the pack carburizing system.

The steels used for forgings that are to be carburized generally have a carbon content in the range of 0.08–0.25 %, as for example, in ASTM Specification A 837, Steel Forgings, Alloy, for Carburizing Applications. Since the carburizing operation is carried out in the austenitic temperature range, the heat treatment of carburized forgings must take place after carburizing, by quenching directly from the carburizing furnace as is possible with gas carburizing, or after reheating for pack carburized forgings. Because of the significant difference in carbon content between the case and the core materials, a double quenching cycle is sometimes used whereby the initial austenitize is done at a higher temperature consistent with the core carbon level for grain refinement, followed by oil quenching, and the second austenitize is done at a lower temperature more consistent with the carbon level of the case, and again is followed by oil quenching. Oil is used because of the high carbon content of the carburized surfaces. Because the object of the carburizing operation is to obtain a hard surface case, tempering after quenching is done at low temperatures of the order of 150–400°F (65–205°C), although in some instances the parts may be used untempered. Carburized case depths are usually appreciably deeper than those obtained in nitriding, commonly being about 0.05 in. (1.25 mm), but can be as thick as 0.25 in. (6 mm) in some applications. Various types of gears and some bearing races are made from carburized forgings. Unless heat treated in a controlled atmosphere or in a vacuum, slight decarburization will occur during hardening, particularly if the double quenching method is used, so that hardness checks should be done after surface grinding.

As in the case of induction hardened surfaces, great care must be taken during the grinding of case hardened areas to avoid grinding cracks.

Salt Bath Treatments

Molten salt baths are used for some heat treatment and surface treatment operations. Generally, their use is limited to smaller forging sizes. The baths may be externally heated by oil or gas burners or by electric resistance heaters. Internal heating by the use of electrodes is used also. The salt material may be neutral for operations such as martempering and austempering, or may be active for surface treatments such as liquid carburizing, liquid nitriding, and cyaniding. Many of the compounds used in salt baths are toxic, and both storage and disposal of the constituents even from neutral baths have become difficult and expensive.

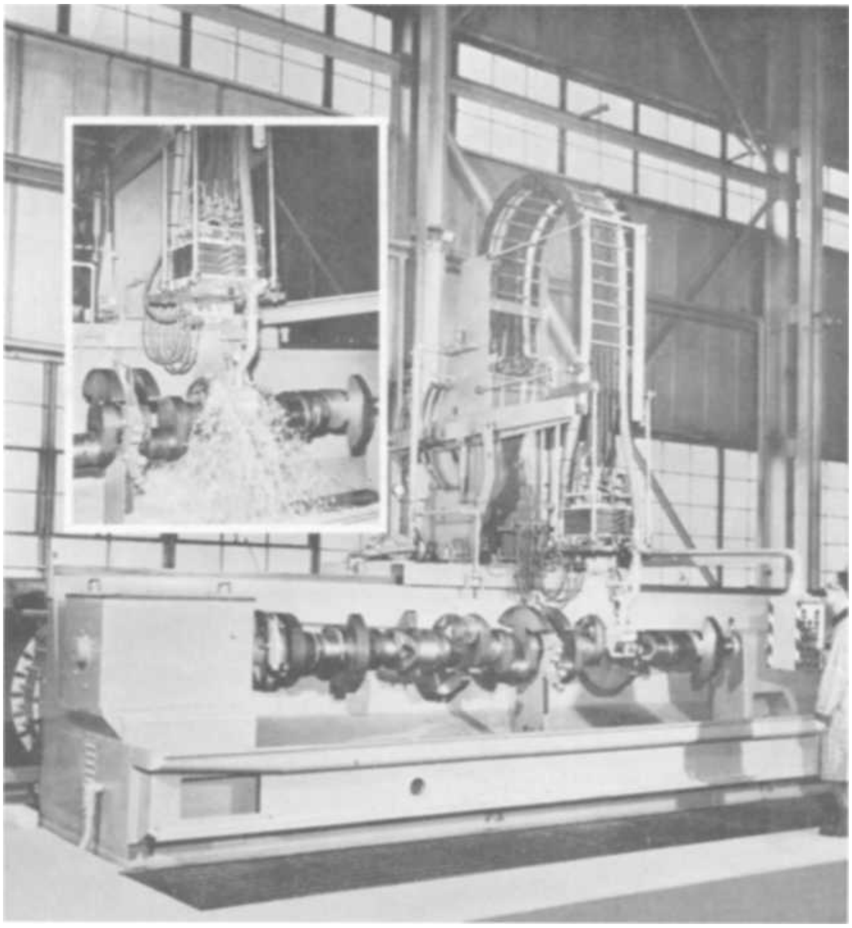

Fig. 12.4—Induction hardening machine for diesel electric locomotive crankshafts. The main and crankpin journals are hardened individually while the shaft is rotating. The inset shows the quenching stage. The quenching ring is integral with the induction coil. (Courtesy Ellwood National Crankshaft Company)

Cold Working

Except for the austenitic stainless steels and some cold forging applications, cold working as applied to steel forgings is generally a surface treatment used to enhance fatigue strength, and is often referred to as peening or shot peening. The idea is to establish a helpful residual compressive stress in the surface layers in selected areas of a component, such as the bearing fillets of an axle or a crankshaft. Close control of such an operation is required to assure that the required extent and reproducibility of the cold working has been achieved. The cold working can be accomplished by means of pneumatic peening hammers, mechanically applied rollers, or by controlled surface blasting using compressed air and carefully selected shot material. To be effective on a repetitive or production basis, specialized equipment is required. Specification A 504/A 504M, Wrought Carbon Steel Wheels, includes a requirement for the shot peening of the running surface according to the SAE Specification, J443, Recommended Practice for Procedures for Using Standard Shot Peening Test Strip.

The cold working of the austenitic stainless steels is used to significantly increase the yield strength through the cross section, without significantly reducing the ductility or notch toughness of the material. The cold working can be done by the use of a steam hammer or under a press, and need not be done cold. Although the yield strength of type 304 stainless steel can be increased from a minimum of 30 ksi (205 MPa) to 45 ksi (290 MPa) in section sizes up to 10 in. (250 mm) by this method, for example in submarine periscope tubes, there are few if any commercial forging specifications that employ it.

Cold forging, commonly using rotary forging machines, is used for some of the smaller size applications in the automotive field for items such as power steering valve bodies and transmission components, as shown in Fig. 5.10. The process is also used in the production of rifle barrels to the extent of forming the bore rifling.

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13

Manufacturing Problems and Defects

DEFECTS IN FORGINGS CAN STEM FROM VARIOUS sources that need to be recognized to prevent occurrence or recurrence:

- Base material choice and manufacture
- Ingot defects
- Ingot size and choice
- Billet/bloom size and source
- Heating for forging and Forging Temperature Range
- Induction Heating
- Forging operations and machining
- Post forge handling/heat treatment

Base Material Choice

Most steels can be forged, but some of the tool steels such as D2 can be difficult to hot work because of the coarse carbides, and this problem tends to get worse as the ingot size increases because of the as-cast coarseness. Light initial working of the ingot surface, sometimes referred to as *Packing*, can assist by breaking down the initial columnar structure and improving the hot ductility before taking more aggressive forging reduction. Initial surface cracking will oxidize and hinder repair by forge welding, whereas some subsurface material tearing under the initially worked layer can heal under compressive working conditions.

For some of the more difficult materials, the forging of preforms made from powder compacts that have been consolidated by hot isostatic pressing has been a successful route. Gas turbine rotor disks have been produced this way by isothermal closed die press forging in a special installation that is used under vacuum.

Hydrogen in the steel is another ferritic base material related hazard that, while not a problem during the actual forging operation, manifests itself as fissuring or *flaking* of the forging at some time after transformation from the austenitic phase. This was discussed in Chapter 3 under vacuum degassing in the steel making section. Some steel grades are much more prone to flake than others. The nickel-chromium-molybdenum alloy steels are very susceptible, as are the medium carbon steels and the age hardenable copper-nickel-chromium-molybdenum low alloy steels included in Specification ASTM A 859/A 859M, Age-Hardening Alloy Steel Forgings for Pressure Vessel Components. Generally to avoid long expensive hydrogen diffusion cycles, hydrogen in the molten steel has to be held to less than 2 ppm, but for the very susceptible steels the aim should be to keep hydrogen under 1.5 ppm. Although extremely important, hydrogen limits do not appear in national material specifications because of the variations that occur between different types of sampling and hydrogen measuring equipment. The time of sampling is also important. One method of sampling is to suck a small molten steel sample into a glass tube while ingot teeming. The pin sample is broken out of the tube and refrigerated immediately in liquid nitrogen to fix the hydrogen. Determination of the hydrogen content is then done by fusion using standard sample pins for calibration purposes. Another system collects the steel sample in an evacuated steel cylinder. Hydrogen given off the sample during solidification is trapped in the cylinder and is drawn off and measured when the cylinder is pierced in the measuring equipment. Dissolved hydrogen is determined from the sample by fusion, and both values are added to give the total hydrogen in the liquid steel at the time of teeming. Yet another system measures the hydrogen in the ladle, and gives the total value. Hydrogen in steel increases when melting is done under high humidity conditions, so that hydrogen values tend to rise during hot humid weather. Ladle additions after vacuum degassing are another important hydrogen pick up source and this must be carefully monitored. Most ladle refining furnace (LRF) systems permit further vacuum degassing after additions if this is felt to be advisable; however, in simple electric furnace/vacuum degassing processes where reheating is not possible, making additions to the ladle after degassing, or for that matter to the mold, presents a definite risk of hydrogen pick up. Exceptions to this are the vacuum lift degassing systems that permit ladle additions under vacuum, and the ladle to mold vacuum stream degassing procedures. Aside from hydrogen dissolved in the steel as it comes from the ladle, later pick up points include the ingot molds, and mold coatings.

Ingot Defects

Ingot defects that affect forging include piping and other centerline shrinkage voids, longitudinal and transverse cracking, and exogenous inclusions. It should be noted also that factors such as teeming rate and temperature are vital factors in ingot production.

Piping is a longitudinal void usually on or near the ingot vertical axis caused by insufficient feeding from the hot top. This is commonplace in big end down ingots poured without hot tops. Occasionally secondary piping, removed from the hot top, is encountered in forging ingots. This is associated with bridging over the shrinkage area during solidification, and is sometimes a result of prematurely stripping the ingot from the mold. This problem can be associated with a low teeming temperature also.

With the advent of bottom pouring, round ingots with a very small degree of taper from top to bottom (to assist in stripping) have become popular for forging and extrusion applications. At diameters upwards of 24 in. (600 mm) there is an increasing risk of piping for the full length of the ingot. For example, with an ingot diameter of 30 in. (750 mm) a full length pipe of about 2 in. (50 mm) in diameter has been observed.

Longitudinal cracking of bottom poured ingots, particularly the plain round cylindrical type, is associated with an excessive rate of rise in the mold. It may also occur in high hardenability steel ingots that have been left in the as cast condition for some time after stripping, and this neglect is another likely source of cracking during the reheating stage for forging.

Circumferential Cracking, particularly when located near the top of the ingot, can be caused by failing to permit the hot top to subside as the ingot cools after top pouring. For example, some hot top designs use refractory lined cast iron forms that are set down into the mold. The weight of the ingot can be adjusted by varying the position of the hot top form. This setting is made by holding the hot top in position by means of simple wooden sticks of an appropriate length. The molds shown in Fig. 13.1 use this procedure. After teeming the ingot, these sticks must be removed to permit the hot top to settle during cooling. Failure to do this imposes a longitudinal tensile stress on the ingot that causes circumferential hot tears called hanger cracks. Hot top hangers for other hot topping systems can cause similar cracks.

Pouring Interruption during teeming can produce a circumferential weakness in the ingot, or in the case of bottom pouring, in all of the ingots on the same bottom pouring plate. A similar problem can occur in VAR and ESR ingots if the power supply is interrupted during remelting. Such conditions are unlikely to be healed during subsequent forging because of oxidation during heating to the forging temperature.

Ingot centerline problems, such as interconnected shrinkage voids and including piping, may or may not be significant, depending on the product being made. If the forging is a solid, such as a turbine rotor or a heat exchanger tube sheet, then the soundness of the ingot center is of great interest, and one must be certain that the subsequent hot working operations will heal any voids and yield an acceptable forging on ultrasonic examination. This applies particularly if the component is to be given a small bore, when cleanliness in a magnetic particle examination is added to the ultrasonic acceptance criteria. If the solid forging is to be bored, as would be the case for a piping fitting or a pressure vessel shell, then central soundness is of little concern, since the core will be removed. For a hollow forging produced by working over a mandrel after hot trepanning, the

Fig. 13.1—Forging ingots being top poured. The ingot to the front left foreground has been teemed and the hot top supports removed. The wooden supports are fitted between the cast iron hot top case and the top of the ingot mold before teeming begins. These maintain the hot top position until the mold has been filled, but must be removed immediately afterwards to permit the hot top to settle.

axial ingot core is removed at the forging stage. It should be noted, however, that for a hollow forging produced by hot punching, that is pushing a solid punch through the billet to produce the initial bore, the ingot core material is not directly removed, but is spread along the bore of the forging. However, at least some of this material should be removed during subsequent machining.

Exogenous Inclusions are associated with foreign material in the ingot and may come from oxidized material from around the ladle nozzle falling into the mold, a hot top hanger strap, or from a tilted splash plate used to protect the bottom of a top poured mold. Such material, often referred to as exogenous, may not be found until late in production of the forging and can be expensive in terms of replacement costs and production time. Good housekeeping in the meltshop is essential.

Teeming Rate is critical during bottom pouring, being slow enough to avoid the risk of longitudinal cracking, particularly in plain round ingots, and at the same time avoiding the possibility of freezing off during teeming. Usually, a ladle scale is used to regulate the rate of rise in the molds.

Teeming Temperature is a vital variable in ingot production, regardless of the teeming method used. Although too high a temperature is objectionable, low teeming temperatures are disastrous for forging quality, because of widely dispersed inclusions that would otherwise have floated to the top of the ladle.

Ingot hot tops provided a reservoir of molten steel that permits feeding of the ingot during solidification to eliminate or at least significantly reduce piping and shrinkage. Some form of insulating material such as vermiculite is used to cover the top of the ingot after the hot top has been filled and has crusted over. This is intended to slow solidification from the top. Exothermic compounds have been used also for this purpose, but inclusion studies for some large rotor forgings have indicated that exogenous material from this source can be carried down into the solidifying ingot [1], so that this technique has to be used with caution.

Ingot Size and Choice

Generally, a steel forging ingot is regarded as being of the big end up type in which the mold is tapered, the cross section being larger at the top than the bottom. The cast iron molds are generally round and fluted to reduce the risk of ingot surface cracking. Some of the smaller molds are square or rectangular in cross section and may have fluted or plain sides. As previously mentioned, the molds have provision for hot topping, an essential component in forging ingots. The amount of steel in the hot top of a forging ingot can be 30 % of the ingot weight and, as well as acting as a tong hold, forms part of the ingot discard taken when making the forging. For many years forging ingots were top poured. Aside from reoxidation possibilities when teeming in air this practice tends to cause erosion of the mold wall and can lead to stripping difficulties. Although more expensive in terms of refractories and equipment, the current preferred practice is to use bottom or uphill pouring. This is done by teeming from the ladle into a refractory lined sprue or stem and feeding the steel through refractory tubes into the bottom of the ingot mold. An example of this for VAR electrodes is shown in Fig. 4.4. In this way a single ingot, or a group spaced around the sprue on a steel plate, can be poured. The ingot molds can be of different cross sections, but obviously for a given plate the level or height of the steel will be the same for all of the molds. The rate of rise in the molds is very critical, and ladle scales are used to control this parameter. The straight-sided cylindrical molds are teemed in this fashion.

Bottom poured ingots generally need less hot top volume than top poured ingots, so that the ingot yield is improved, although some of the ingot may have to be used for the forging tong hold. The ingot surface condition is much better in bottom pouring compared with top pouring, in part because of the glass-like mold flux that is used. While being helpful for extrusion, and possibly in making billets for forging, the significance of this depends on the degree of machining that is involved in making the final forged component.

As a rule of thumb in the interests of forging quality, the preference is to use the smallest ingot that is consistent with the required forging reduction.

Regarding forging yield from an ingot, this largely depends on the type of forging and the degree of machining required to make the forging, and can be quite small. An extreme example is the submarine diesel crankshaft shown in Figs. 2.14–2.19.

The original top poured 42 in. (1050 mm) octagonal ingot weighed 44 000 lb (20 t).

Slab forging weight:	21 400 lb (9700 kg)
Discard and scale loss by difference:	22 600 lb (10 250 kg)
Finished crankshaft weight	5504 lb (2497 kg) or 12 % of gross ingot weight

Billet/Bloom Size and Source

Many forgings both large and small are made from wrought billets or blooms. These terms are almost interchangeable, but billets are generally regarded as being smaller in cross section than blooms. Both are considered to be round or square, as compared to slabs that are distinctly rectangular in cross section. Blooms and billets must be hot worked and may be produced by forging or rolling. Continuously cast material is frequently used for the supply of material for billets or blooms for forging, but it is important to recognize that the product coming directly from the caster will not have been hot worked, so that the material is the equivalent of ingot cast forging stock. Progress has been made in improving the macrostructure of continuously cast steel. A cross section reduction ratio of 2.0:1 has been permitted in Specification A 20/A 20M, General Requirements for Steel Plates for Pressure Vessels, for rolled plate 3 in. (75 mm) or more in thickness, rolled from continuously cast slabs, conditional on several added restrictions including a sulfur limit of 0.010 % maximum and through thickness tension testing.

Since billets and blooms are commonly supplied in cut lengths, the presence of central pipe may be detected by examination of the end faces. Removal of surface seams by grinding before forging is an option.

The efficient operation of continuous casters involves the uninterrupted use of back-to-back heats of steel. Where this involves the same grade of steel, the mill is required to use its own procedures to identify the individual heats. When a change of grade occurs, the transition material is separated from the production run. In the case of forging stock, this identification should be traceable after heating for forging. Heat resisting steel tags are often used for this purpose. Identification of the ingot top and bottom locations is very desirable for forgings, because of discard requirements and quality monitoring. Although easy to do for forging ingots and blooms or billets forged directly from ingots, this may not be possible for forging stock cut from strand cast material.

Vacuum arc remelted ingots are generally sound, but it has been noted that if the primary heat for the electrode was calcium treated for inclusion shape control—something that is unnecessary for consumable electrode remelting—then near surface pockets of white calcium bearing powder could be encountered in the VAR ingot.

In electroslag remelted ingots (ESR) calcium treated electrode material is less of a problem because of melting through the slag, but for hydrogen sensitive grades, great care has to be taken to avoid hydrogen pick up during remelting. The hydrogen content of the parent heat must be kept to very low levels, and dry air systems are used around the ESR furnace. This is important, since it is not possible to obtain meaningful hydrogen contents for the remelted steel. Close control of the ESR slag composition is also very important to avoid excessive aluminum pick up from the slag. Instances have been reported, where, because of high aluminum pick up from the slag during the remelting of high carbon steel grades, graphitization in the remelted material rendered it useless.

Heating for Forging

The heat to forge operation can be done in different ways in batch or continuous furnaces and by induction heating. It is a vitally important operation, since the integrity of the forging literally hangs on this operation being properly executed. The hot working operation is carried out in the austenitic temperature range for ferritic steels, where plastic deformation is done above the recrystallization temperature. Generally, as the hot working temperature is increased, the strength of the steel decreases, ductility increases, and the force or power required to work the steel decreases. The austenitic grain size of the steel also increases as the hot working temperature is raised. For some steel compositions a dip in ductility, as measured by reduction of area, occurs at high temperatures, and such a temperature zone would not be favorable for hot working. Besides increasing scale formation as the hot working temperature is increased, and possible intrusion into a low ductility zone, at very high hot working temperatures severe grain growth becomes a serious problem that affects the mechanical properties of the finished forging. This leads to a condition known as *Overheating* and requires the use of additional heat treatment steps to effect adequate restoration of properties by refining the grain size. A step beyond overheating results in grain boundary oxidation and incipient melting of lower melting constituents in the steel. This is known as *Burning* and this condition is irreversible. The mechanical properties of the steel are severely impaired, including tensile and yield strengths, ductility, and toughness. The fatigue strength of the steel is significantly reduced also with the presence of the oxidized grain boundaries at highly stressed surfaces, presenting undesirable stress concentration sites. Forgings that have been burned during the heat to forge stage are fit only for scrap for the electric furnace. An example of a burnt alloy steel is shown in Fig. 13.2.

What then are the acceptable temperatures for forging for most engineering steels? The major advantage of high forging temperatures is for ease of forging, and that translates into reduced time between the dies, potentially improved productivity (and perhaps higher bonuses), and less strain on the press, or alternatively increasing the size range of a given forging press. It follows then that the forging crew, including the immediate supervision can be expected to opt for the highest forging temperatures. The metallurgical support will take a more balanced view and opt for a general forging temperature for most carbon and alloy steels of no more than 2250°F (1230°C). This will be qualified by considering the nature of the particular forging operation to be done. If, for example, an ingot upsetting operation is required, this is a preliminary hot working stage, and depending on the ingot size and press capacity, may be taxing the equipment capabilities so that a temperature of 2350°F (1290°C) would be acceptable, given that further work at lower temperatures will be done. Certainly 2400°F (1320°C) would be looked at askance.

Burning has been identified at 2470°F (1355°C), but the onset may take place at lower temperatures when the time element is taken into account and particularly in segregated areas. Another variable is the actual piece temperature in a furnace operating at these high temperatures, bearing in mind the day-to-day operational status, furnace loading, condition of individual burners, thermocouples, furnace sealing, bolster condition, and so on, that can give rise to local hot spots or temperature aberrations. An important aspect here in terms of uniformity is even heating of the ingot or billet. A temperature gradient, particularly across the piece as opposed to end to end, can lead to throwing the axis of the ingot off the axis of the forging and lead to dimensional problems in the forging, because of one side being easier to move than the other, a condition known as being cold sided. For a forging, such as a turbine rotor, displace-

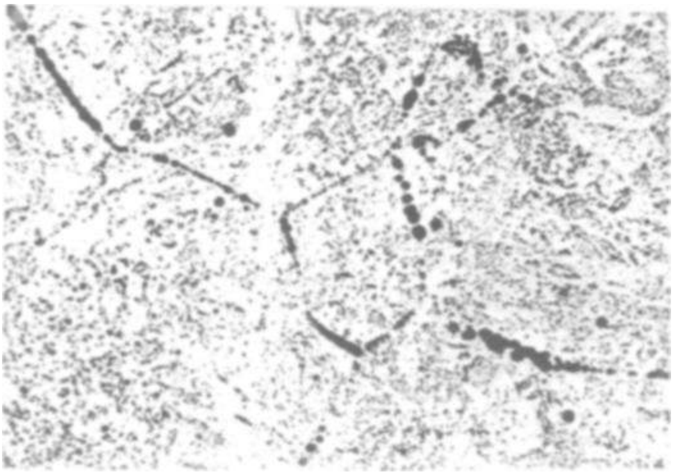

Fig. 13.2—Microstructure of a burnt Ni-Cr-Mo steel showing grain boundary oxidation and incipient melting. A classic feature is the triple point formed where three grains meet and slight melting and boundary oxidation effects are present. These often would be apparent on a micro-polished surface. Nitro-sulfuric etchant. Original magnification ×100.

ment of the ingot longitudinal axis can manifest itself later in the form of bowing under heat during a heat indication test. This phenomenon is sometimes caused by residual stresses and can often be cured by stress relieving; however, a displaced ingot axis may well lead to rejection of the rotor, since it could cause the turbine blades to rub against the turbine steam chest.

For large forgings it may not be possible to complete the forging in one heat. This is particularly the case when an upsetting operation is involved, or when an operation such as hot trepanning is required. In such cases, the reheat temperature chosen is lower than the original temperature. For example, if 2350°F (1290°C) had been used for the upsetting operation, then 2250°F (1230°C) could be used for the first reheat. However, when relatively little forging work remains to be done and a reheat is necessary, then an appreciably lower temperature would be chosen, such as 2100°F (1150°C). An important reason for this is that it is highly desirable for most materials to aim for a low finishing temperature of less than 1700°F (925°C), bearing in mind that the measured temperature is at the surface, and that the core temperature will be higher.

Induction Heating

Induction heating for forging is now fairly common, particularly for repetitive forging operations. Temperature control for induction heating must be taken seriously, given the rapid heating rates possible with this system. It should be remembered that the temperature of the billet is related directly to its initial temperature and the electrical power input to the induction coil. Commonly, the induction heater is set up to use a specific wattage for a given billet size and weight, based on the billet being at ambient temperature at the outset. The controls downstream of the induction coil can detect a billet temperature outside of the required range, and eject the billet from the line. The billet is allowed to cool and is fed back into the system. If the billet is still warm when it enters the coil again, the exit temperature will be higher than intended and the risk of burning is increased. In induction heating lines, optical pyrometer systems are generally used and these must be kept clean and maintained. Cross-linked back up systems are advisable. For large cross sections such as, for example, a 7-in. (175-mm) diameter bar, and depending on the current frequency, the currents induced by the coil are restricted to the near surface, perhaps from surface to about 2 in. (50 mm) deep, so that heating of the important bar center depends on conduction. It is possible for very high temperatures to be reached in the near surface zone before the center comes up to the required temperature, and to counter this, a soak time with little or no power input is required during the cycle to permit the temperature to equalize. If this is not done the bar may be forged with the center temperature low enough to result in internal bursting, or severe overheating of the surface may be occurring as the core comes up to temperature.

Forging Operations and Sequence

Forging operations, themselves, should not cause problems if the temperatures are properly controlled and ingot or billet difficulties have been avoided. In general, heavy forging drafts on as cast material may not be advisable early on in the operation to avoid surface ruptures and tearing. Some of the more highly alloyed steels require a more gentle surface packing operation of the ingot before proceeding to more aggressive passes. Care should be taken to avoid forging laps and seams, particularly in closed die operations. Dimensional errors are probably the most common; for example, the wrong distance between collars or flanges when forging shafts may be caused by layout errors at the press or in making the forging drawing. Certainly layout at the initial open die forging stages is most important, and if not done properly can result in having insufficient material to properly complete the forging or risk having top or bottom discard material included in the part. As discussed in the ingot section, allowance must be made to permit removal of material from the top and bottom of the forging ingot to minimize the presence of objectionable segregates and inclusions and, from beneath the hot top, shrinkage voids. This discard may be taken off during the forging operations, or following completion of the hot work. In an integrated melting/forging facility, this discard material becomes heavy scrap for a future heat of steel. In a forge shop without melting facilities, the discard must be sold to a steel maker as furnace scrap together with material—referred to as turnings, chips, or swarf—removed during machining. This forms a part of the economics of the process.

Machining

In boring and many finishing operations, oils are used for the lubrication and cooling of the tools, as well as transporting the chips away from them. An appreciable amount of this oil is entrained with the chips, and should be recovered in preparing the chips for scrap. This can be done by centrifuging, thus reducing the smoke generated during remelting in the furnace. Since many machining oils contain significant amounts of sulfur, this could become a source of contamination during subsequent steel making.

Baling of the chips or swarf reduces the volume for scrap shipment, and enables more to be used in the furnace charge.

Segregation of the chips or swarf by material grade, while of major importance in an integrated forge shop, should be addressed also by those who purchase steel and sell the chips produced as scrap. The reasons for this include minimizing the presence of tramp or unspecified elements in the steel, especially important where the specification imposes limits on such elements, and the economic loss in "giving away" expensive alloying elements such as nickel and molybdenum.

Post Forge Handling/Heat Treatment

On completion of the forging operation the temperature of the part is hopefully lower than 1800°F (1000°C) and possibly as low as 1500°F (815°C) on the surface. For the ferritic steels transformation is the next stage in cooling. If the remnants of the hot top, now a tong hold, and the ingot bottom plug or bottom pour runner are still attached, these may be removed by flame cutting, taking advantage of the remaining heat in the forging. If this is the case, some idea of the temperature gradient from surface to core can be obtained from the shades of red that are exposed.

Practices in the handling of forgings at this stage vary from forge shop to forge shop, depending on the product mix, materials used, and steel source, but the object is to economically and safely get the forging to the next production stage. Aside from the risk of hydrogen flake formation, keeping residual stress to a minimum in heavy forgings is also an important consideration, particularly when dealing with high carbon low alloy steels, such as those used for some steel mill work rolls. For this purpose, the forgings are allowed to transform and cool slowly and evenly before being given a post forge heat treatment cycle.

As an optimum, this cycle will consist of equalizing the temperature of the forging in a furnace operating at a low subcritical temperature of perhaps 600°F (315°C), then heating it at a rate of about 120–150°F (65–85°C) per hour to an austenitizing temperature of 1650–1750°F (900–955°C), and soaking for a half to one hour per inch of maximum section size, followed by cooling in still air. Heating to a subcritical temperature of about 1250°F (675°C), depending on the grade, and again cooling in still air or in the furnace would complete the process.

For many properly vacuum degassed low alloy steels a subcritical anneal, typically at 1250°F (675°C), following slow cooling from forging is adequate. For the flake sensitive grades, and particularly if the vacuum degassing treatment is suspect, an extended hold at the subcritical temperature may be necessary to give adequate opportunity for hydrogen diffusion.

The power of high residual transformation stresses in large diameter forgings should not be underestimated. For example, a large hypereutectoid alloy steel work roll broke in two in a lathe during rough machining, and continued to subdivide itself on the floor for some days afterwards as a result of internal fractures related to hydrogen and high residual stresses.

In some cases, for example, in vacuum degassed carbon and certain alloy steel forgings, even large pieces can be allowed quite safely to cool to room temperature without any specific postforge heat treatment, and proceed through machining to final quality heat treatment for mechanical properties. This relates to effective vacuum degassing and the steel composition. Heavy section forgings in the F22 grade, 2¼Cr1Mo, have been handled this way after forging, and the material was noted to be less "gummy" during machining, compared to those that had received a postforge heat treatment.

For the alloy steels, particularly those of high hardenability, the final subcritical annealing treatment after forging is necessary for machinability purposes also.

In some cases especially, for the smaller closed die forgings, the final quality heat treatment is given in the as forged condition.

In Chapter 10, the reduction of area measurement from the tension test was discussed. It is worth repeating here that hydrogen levels low enough to avoid flake damage can cause reduced tensile ductility in heat treated forgings, without significantly affecting the tensile and yield strengths, and without noticeable effect on Charpy absorbed energy. In this circumstance, the tension test fracture faces will usually exhibit "fish eyes" as shown in Fig. 10.1. In this example, for a Grade 2 forging to A 508/A 508M the ductility was restored by heating the forging at 500°F (260°C) for 168 h for a 16-in. (400-mm) heat treated section size.

References

[1] Kim, J., Lee, M., Kwon, H., Chang, H., Kim, J., and Yu, I., "Manufacturing Technology and Mechanical Properties of the Mono-Block LP Rotor Forgings," *The 14th International Forgemasters Meeting*, Wiesbaden, Germany, October 2000, pp. 171–176.

14

A Word about ASTM International, Committee A01 on Steel, Stainless Steel, and Related Alloys, and General Requirement Specifications for Forgings

ASTM WAS FORMED IN 1898 AS THE AMERICAN Society for Testing and Materials with a nucleus of 70 members. An extract from the original charter states:

> The corporation is formed for the promotion of knowledge of the materials of engineering, and the standardization of specifications and the methods of testing.

Committee A01, the first of the technical committees, celebrated its centenary in 1998. The initial steel standards, some of which are still current, were written for the burgeoning railroads to cover materials for track, locomotives, and rolling stock.

Details of Committee A01 on Steel, Stainless Steel, and Related Alloys are published in a booklet entitled Facts for Members, published on the ASTM web site: http://www.astm.org.

ASTM International Committee A01 currently has 19 technical subcommittees set up to write and maintain specifications for various steel and stainless steel product forms, such as castings, rod, wire, tubes, pipes, sheet, plate, and forgings. Additionally, several support subcommittees cover such aspects as terminology, editorial aspects, liaison, and administration. The responsibilities for some product forms are further broken down depending upon application, such as structural or pressure retaining.

Writing Standards

A word may be in order here to explain the ASTM International standards writing process. A technical committee is first formed under the Society umbrella from volunteers consisting of producers, users, and a category known as general interest. The latter includes people from academia, government, and consultants who are not supported by the producers. A committee scope is agreed upon and subcommittees and task groups are set up to start the specification writing activity. The committee operates under established rules, including Robert's Rules of Order, and usually meets twice a year to consider the results of balloted actions, and respond to requests for writing new standards and making revisions to existing standards.

Task groups are set up to write the required standards, and once the draft of a new standard has been completed, it is subject to a subcommittee ballot. Comments and negative votes on the draft are considered according to the rules of the Society, and if necessary, the draft is revised and reballoted in the subcommittee. Following successful subcommittee ballot, the draft proceeds to a main committee ballot, when all members of the committee have the opportunity to vote on it. Again, any comments and negative votes are considered. Revisions stemming from this ballot, if they are considered to be more than editorial in nature, result in the whole process being repeated with a further subcommittee ballot, followed by another main committee ballot. A Public or Society ballot is included in the process, and from there the draft goes through an editorial survey prior to publishing. ASTM oversight committees ensure that any negative votes have received due consideration. The sub and main committee makeup is such that the producer voting membership cannot exceed the sum of the user and general interest voting groups.

Committee A01 gives editorial support to the technical subcommittees through Subcommittee A01.91. This subcommittee, while maintaining A 994, Standard Guide for Editorial Procedures and Form of Product Specifications, for Steel, Stainless Steel and Related Alloys, also is responsible for the Facts for Members handbook.

ASTM International Steel Forging Standards

Like many national steel standards from countries around the world, ASTM International publishes specifications for different classes of product form and broad application, but uniquely the Society also publishes standards for specific particular applications. The standards writing system permits specifications to be developed, or revised quickly as application needs arise, avoiding the one book fits all approach used in some countries. This flexibility and expertise has resulted in the global use of ASTM International's standards.

The scope clause at the start of each standard is an important, though often neglected section. It explains the purpose of the standard and often includes limitations such as material thickness or application. When specific restrictions are ignored the material produced to the standard may not be in compliance, and the quality assurance provisions of the standard may be inadequate for the new application. While construction codes sometimes permit the use of material for applications that are not included in the product specification scope, the end user is expected to assure him or herself that the application is acceptable, and therefore, should be familiar with the proposed specification. When it is proposed to use a standard outside of the intended application, this should be remembered.

The steel forging specifications fall into several categories to serve a wide industrial range in the application of steel. These include boilers and pressure vessels, critical rotating machinery components such as gas and steam turbine rotors and wheels, generator rotors and crankshafts, as well as components for piping applications, bridges, cranes, railways, automobiles, offshore oil platforms, steel rolling mills, paper mills, chemical plants, ships, and aircraft. In addition, there are special test methods and practices, including portable hardness testing, magnetic particle and ultrasonic examinations, and dimensional stability tests for steam turbine rotors.

Most of the steel forging standards writing activity was assigned to Subcommittee A01.06 on Steel Forgings and Billets. This subcommittee currently is responsible for over 50 specifications, test methods, and practices [1]. In addition, Subcommittee A01.22 on Steel Forging and Wrought Fittings for Piping Applications and Bolting Materials for Piping and Special Purpose Applications is responsible for ten steel-forged product specifications associated with fittings and flanges for piping systems [2].

General Requirements Specifications

When a large number of product specifications are written, it soon becomes apparent that certain basic provisions for a particular product form become repetitious, and it is important for the sake of uniformity and clarity that these should be addressed fully. The use of general requirement specifications enables this to be done succinctly. Furthermore, the use of such standards facilitates revisions that would otherwise have to be made individually in each affected product specification, and enables changes (for example, in steel making practice) to be incorporated quickly, thus keeping the associated system of standards current with established industry practice. The drawback to the use of these general requirement specifications is that they must be read along with the required product standard in order for the reader, be it purchaser, producer, or oversight inspector, to understand what is required to be done. Although attention is drawn to this in the individual product standards that use general requirement specifications, the significance of the general requirement specification may not always be appreciated and is worth stressing.

It is acceptable to order material to revisions of an ASTM product specification that predate the current version, identifying the required revision by year date and suffix letter, if any. However, for the relevant general requirement specification, the consensus is that the version that is current at the time of order placement should be used, unless specifically ordered otherwise. This is because the supplier's quality assurance system would be expected to be set up for the current general requirement specification revision, and earlier revisions that perhaps match the year date of the product specification may not be available.

General Requirement Specifications for ASTM Steel Forging Specifications

For the ASTM steel forging specifications the two relevant standards are:

- A 788, Steel Forgings, General Requirements. This standard is maintained by Subcommittee A01.06.
- A 961/A 961M, Common Requirements for Steel Flanges, Forged Fittings, Valves, and Parts for Piping Applications. This standard is maintained by Subcommittee A01.22.

These specifications will be discussed together in detail before addressing the individual product standards.

A 788-04 Steel Forgings, General Requirements

The scope clause defines the order of precedence between the product specification and the general requirement specification in the event that a conflict should exist between the two. Another important part of the A 788 scope concerns the certification and marking of forgings that are to be supplied (at the request of the purchaser) without all of the specification provisions having been completed. For example, there might be a situation whereby the purchaser is better able to complete a final machining operation that is necessary before a required ultrasonic examination can be done. In this case, the final certification and marking of the forging would be done, either by the forging supplier or the purchaser, after delivery and completion of the necessary test.

The Terminology section is an important part of ASTM standards in general and particularly for general requirement standards. Committee A01 has a Terminology Subcommittee A01.92, and this group is responsible for the Standard A 941 Terminology Relating to Steel, Stainless Steel, Related Alloys and Ferroalloys. This standard is an active compilation of definitions and terms that are applicable to the work of Committee A01; however, specific product specifications may include terminology that is not included in A 941, because of limited application, or because it differs from the more common usage. The practice is that definitions are kept short, preferably to a single sentence, but they may include a *discussion* that provides additional information. This discussion is a mandatory part of the definition.

In Specification A 788 the terminology section includes the definition of a forging, and this was quoted in Chapter 1. This definition began in 1964 as a standard in its own right as A 509, Standard Definition of a Steel Forging, and although quite short, was the product of considerable discussion in the subcommittee. The terminology section also deals with subjects such as ingots, strand or continuous casting of steel, and the intercritical heat treatment of low hardenability carbon and low alloy steels. The terms "billet" and "bloom" are stated to be interchangeable, rather than defined by size, and an important distinction is made between wrought and as cast material supplied as billets or blooms. The as cast material must be supplied as *cast* billets or *cast* blooms.

The Ordering Information section addresses the minimum information that is considered to be necessary for the supply of a steel forging. This is intended to help in the writing of an inquiry or purchase order, but does not address items such as delivery time or surface finish beyond that required to perform any required nondestructive examinations. Important items such as these are outside the scope of the product specifications but should be addressed in the purchase order and drawing.

Another important function of the purchase order is to indicate when Supplementary Requirements are required. These are adjuncts to the specifications and are intended to add to the basic requirements rather than detract from them; however, they apply only when included in the purchase order, and will be discussed in more detail later.

Written certifications must indicate the product specification number, year date, and any applicable suffix letter, but the year date and suffix letter need not be carried over to the material marking. The certification and marking requirements have been couched in terms that permit the use of the "SA" prefix when forgings are ordered to Section II of the ASME Boiler and Pressure Vessel Code.

The next section, Melting Process, describes the permitted steel making processes for forgings made to specifications written by Subcommittee A01.06. All of the current steel making processes are mentioned, including secondary refining, together with some that are essentially obsolete, at least in North America and Europe. This section includes a description of the common vacuum degassing procedures, because some of the forging product specifications have mandatory vacuum degassing requirements. Some product standards further limit the types of primary melting; for example, by excluding the open hearth process.

For steel ingots produced by a remelting process such as VAR or ESR, the analysis from one remelted ingot (or the product from a remelted ingot) serves as the heat analysis for any other ingots remelted by the same process from the parent heat. A Supplementary Requirement S27 requires that a heat analysis be taken from each remelted ingot or its forged product.

Forging is covered by reference to the definitions included in the terminology section, so that these become a mandatory part of the material specifications. Specific operations or techniques, such as upsetting or hollow forging, are generally left to the forging producer, in concert with the purchaser's requirements, and must take into account the dimensions of the forging, required application and properties, and available ingots or billets. An exception to this is Specification A 471, Vacuum Treated Alloy Steel Forgings for Turbine Rotor Disks and Wheels, where upset forging is a mandatory part of the manufacturing process.

Chemical Composition is a key subject that is detailed in Section 8. The primary chemical requirements apply to the composition of the steel that is present in the ladle immediately before or during teeming into the ingot or, in the case of continuous casting, into the tundish. This *heat analysis* was also known, particularly in Europe, as the *Cast Analysis*, and in Specification A 788 the preferred time of taking the sample is during the ingot pouring or teeming stage. For steel that is vacuum stream degassed, however, a sample taken before degassing will be unsatisfactory because of carbon loss during degassing. If the steel was vacuum stream degassed into a second ladle (ladle to ladle) for subsequent teeming in air, a system used when small VCD ingots are required, then the heat sample can be taken during the teeming process, but if the steel was teemed into a mold in the vacuum chamber (ladle to mold), the heat sample must be obtained from the ingot after the vacuum seal has been broken. For very large forgings it is not uncommon for multiple heats to be used to fill the ingot mold. Sometimes, depending on experience with a particular large mold design, the chemistry of the successive heats is adjusted to compensate for the anticipated chemical segregation associated with the particular ingot design during cooling, particularly at the ingot hot top. The means of arriving at the heat chemistry for such ingots is described in Section 8, and in Annex A2 of the specification.

A special case associated with continuous casting is also described in Section 8. A feature of continuous casting is that not only can one or more continuously cast steel strands be poured from a common ladle instead of teeming a number of individual ingots, but the strands can be sustained by a succeeding heat from another furnace through the buffer of steel in the tundish, remaining from the preceding heat, that is feeding the strands. If the grade or composition of the steel is unchanged, the heat identity of the strand cast material is allocated by the steel maker on the basis of the characteristics of the operating system. This is a part of the quality assurance plan used by the mill. A supplementary requirement (S3) is provided whereby the purchaser can specify that the intermixed steel between heats will be separated and not supplied. In the situation where the steel composition is changed, the strand casting system can continue without a break, but the transition material in the strand must be identified and discarded. Again, the mill procedures are used to determine the extent of the transition stage in the strand.

In the event that there is a problem in securing a heat sample for chemical analysis during teeming, some alternate procedures for obtaining a sample are included in Section 8.

For remelted steel ingots from the Vacuum Arc Remelting process (VAR), or the Electroslag remelting process (ESR), special heat analysis requirements apply. For these remelting processes the composition of the steel in the remelted ingot will vary from that of the parent or primary heat, so that the heat analysis must be obtained from the remelted ingot, or from a product taken from the ingot. A heat number must also be awarded to the remelted ingot. Frequently, more than one remelting electrode will be made from a master or parent heat, and in this case, the heat analysis obtained from one remelted ingot will represent all of the remelted ingots made from that master heat, and assume the same heat number. Supplementary Requirement S27 enables the purchaser to require that a heat analysis be taken from each remelted ingot or its product. The primary heat analysis is not required to be reported, and in fact may not comply with the specification requirements. In the VAR process, for example, a notable loss of manganese occurs during remelting, so that the manganese content of the primary or parent heat may exceed the chemical requirements for manganese for the selected grade.

A similar situation exists for the ESR process where, although there is no manganese loss as happens in vacuum arc remelting, a reduction in sulfur content is expected and the slag can influence the final chemistry.

The steels used for all of the product specifications referenced in Specification A 788 are required to be fully killed.

Product Analysis is another important item that is covered in Section 8. It will be remembered that the heat analysis requirement is obtained from a sample taken from the molten steel just prior to ingot teeming or strand casting. Due to segregation during solidification, or due to variations in the actual analysis results from different laboratories, the chemical analysis obtained from a sample taken from the forging may vary from that obtained from the heat sample. All of the product specifications permit the sampling of the finished material for chemical analysis. This is usually done by the purchaser, but some of the forging specifications (for example, A 508/A 508M and A 723/A 723M) require the producer to take a product analysis and report the results together with the heat analysis. A table of Permissible Variations in Product Analysis for Killed Steel is included in Specification A 788. This table lists the permitted variations, either above the maximum or below the minimum specified values. The size of the deviation depends on the actual specified range for an element, and the cross-sectional area of the forging. The higher tolerances permitted for large cross-sectional areas is intended to compensate for segregation effects in steel coming from large ingots. Certain product specifications, such as A 508/A 508M, have mandatory product analysis requirements that permit no variations for the elements carbon, sulfur, and phosphorus over the maximum values listed in the table of chemical requirements for heat analysis.

An important aspect of the product analysis provisions is that permitted variations cannot be used to extend the chemical requirement ranges in a situation where a sample, taken from the ingot or the forging, is used to obtain the heat analysis.

For a valid product analysis, the sample must be taken from a specific location as described in Section 8. When a product analysis is required to be taken by the forging producer, the mechanical test location is a permitted and convenient site for the sample. When the purchaser wishes to make a valid product analysis, the location must comply with the directions given in Specification A 788. This may not always be easy, but may be possible, for example, when machining weld preparations.

The question of *Residual or Unspecified Elements* is addressed in Section 8. When making steel from a scrap charge, as is the usual case for electric furnace steel making, certain alloying elements that were present in the scrap material making up the furnace charge may not be lost during the subsequent steel making process and will appear in the final steel chemistry. Such elements may not be included in the chemical requirements for the grade in question and are known as residual or tramp elements, or in more recent parlance, unspecified elements. For example, in Specification A 266/A 266M for Carbon Steel Forgings for Pressure Vessel Components, the chemical requirements for Grades 1 and 2 are as follows:

Carbon (max)	0.30 %
Manganese	0.40–1.05 %
Phosphorous (max)	0.025 %
Sulfur (max)	0.025 %
Silicon	0.15–0.35 %

There are no requirements listed for the common alloying elements nickel, chromium, or molybdenum.

Supplementary requirements are included in Specifications A 266/A 266M and A 788 to permit the purchaser to readily specify restricted levels for the elements nickel, chromium, and molybdenum. Other specifications, such as A 508/A 508M, include restrictions for these elements in the table of chemical requirements. It is important to note that for any of the product specifications that reference Specification A 788, when limitations are included for these elements, there is no restriction on deliberately adding them within the prescribed limits. Such restrictions could unfairly impact producers whose furnace charge is associated directly with blast furnace output.

In Section 8 another important requirement regarding chemical composition is the simple statement that *Grade Substitution* is not permitted. In the example above concerning Grades 1 of Specification A 266/A 266M, it is seen that limits are stated only for the elements carbon, manganese, phosphorous, sulfur, and silicon. In a similar but more restrictive specification, A 508/A 508M, there are additional chemistry restrictions for the elements nickel, chromium, and molybdenum. When the chemical requirements for Grade 4130 from Table 2 of Specification A 29/A 29M are examined, it will be seen that these fall within the permitted ranges for carbon, manganese, and silicon, but they also include ranges for chromium and molybdenum. These materials are shown in the following table:

Element	A 266/A266M Grade 1	A 508/A 508M Grade 1*	A 29/A 29M Table 2 Grade 4130
Carbon	0.30 % max.	0.35 % max	0.28–0.33 %
Manganese	0.40–1.05 %	0.40–1.05 %	0.40–0.60 %
Phosphorous	0.025 % max	0.025 % max	0.035 % max
Sulfur	0.025 % max	0.025 % max	0.040 % max
Silicon	0.15–0.35 %	0.15–0.40 %	0.15–0.35 %
Chromium		0.25 % max	0.80–1.10 %
Molybdenum		0.10 % max	0.15–0.25 %
Nickel		0.40 % max	. . .

*** Note: Specification A 508/A 508M also includes a limitation on Vanadium, and in A 29/A 29M this element is covered under the heading of Grain Size.**

It will be apparent that if the chromium and molybdenum contents were to be ignored because they are not specified, that an ingot to SAE 4130 could be applied as A 266/A 266M Grade 1. This would be grade substitution and would not be permissible according to the mandatory requirements of the general requirements specification. The requirements for Grade 1 of Specification A 508/A 508M would prevent this particular substitution.

The forging Marking Requirements (17) of the specification includes the minimum information that is required to be marked on the forging. Note that marking includes the product specification number, as well as the applicable grade, class, and type identifications, but it is not necessary to include the general requirement specification number since the year date and revision letter are not required. While impression stamping is widely used in marking forgings, note that some of the specifications require the use of low stress stamping.

For some applications, the marking requirements are quite extensive and some thought should be given to the marking location on the forging, preferably by purchase order instructions. They should be accessible after installation and not be removed by later machining.

Instructions for the important incomplete forging marking are included in this section. This allows for a situation where a required test would be completed after shipment of the forging to the purchaser. As an example, the purchaser might wish to do the necessary machining prior to the required ultrasonic examination for a forging being produced to Specification A 508/A 508M, so that the final certification and marking would be completed at the purchaser's facilities. Supplemental marking by the use of bar coding is covered in this section also.

Reference has been made to the Supplementary Requirements section of the standard in this review. When the general requirements specification was written, it was found that many of the product specifications included the same supplements such as those covering residual elements or grain size. These common supplementary requirements were gathered together and placed in Specification A 788 where they are available for purchaser use.

Generally, the rule is that a supplementary requirement is intended to add to the requirements of the product specification, not detract from them.

When a supplementary requirement is included in the purchase order, it may have a significant effect on the manufacturing process. For example, if in ordering a forging to one of the grades in Specification A 266/A 266M, Supplementary Requirement S13 on Charpy Impact Tests from Specification A 788 is included, then changes in the manufacturing process such as the use of a quench and temper heat treatment cycle instead of a normalize may be necessary, as well as more extensive machining before heat treatment. Such changes could require discussion with the forging supplier beforehand, since in the case of Specification A 266/A 266M the purchaser must agree to the use of a quench and temper heat treatment cycle.

The Supplementary Requirement lists that are a part of Specification A 788 are worthy of study by the forging purchaser, since they provide a useful means of upgrading a forging to better meet an intended use, as for example S24 for the J Factor in controlling temper embrittlement. As another example, S12 on tension test specimens for hubbed tube sheets could help ensure that the application code requirements are met. The former requires that the element tin be determined for the heat or product analysis, something that may not be part of the product specification, while the latter covers a materials requirement that is somewhat buried in Section VIII, Divisions 1 and 2, of the ASME Boiler and Pressure Vessel Code.

Supplementary Requirement S26 is intended to assist producers in meeting the requirements for forgings used in applications where the European Union Pressure Equipment Directive is in force and includes minimum requirements for the Charpy Impact test, as well as for minimum tensile elongation values based on a gage length of 5D as opposed to the 4D requirement in Specification A 370, where D is the diameter of the tension test specimen.

Although applied only by the purchaser's choice, the supplier should be cognizant of the available supplementary requirements, and be prepared to discuss them with the purchaser.

Specification A 961/A 961M-04a Common Requirements for Steel Flanges, Forged Fittings, Valves, and Parts for Piping Applications

This specification, now in dual format, was written by the Section on Forgings of Subcommittee A01.22 on Steel Forgings and Wrought Fittings for Piping Applications and Bolting Materials for Piping and Special Purpose Applications. The specification is an integral part of nine forging product standards that are intended for the use of the steel pipe fittings industry, and many of these are very widely used. The specification was written to take into account the size range for flanges and fittings used in piping applications, bearing in mind that these items are often manufactured for stock applications.

The Manufacturing section (6) includes some important starting material provisions. The basic premise is that the part will be made from a forging that has been produced as close as practicable to the finished size and shape. This will depend on the method of forging, for example closed (impression) die or open die, and to some extent on the philosophy of the producer regarding time spent under the forging press and the extent of machining. Alternative starting ma-

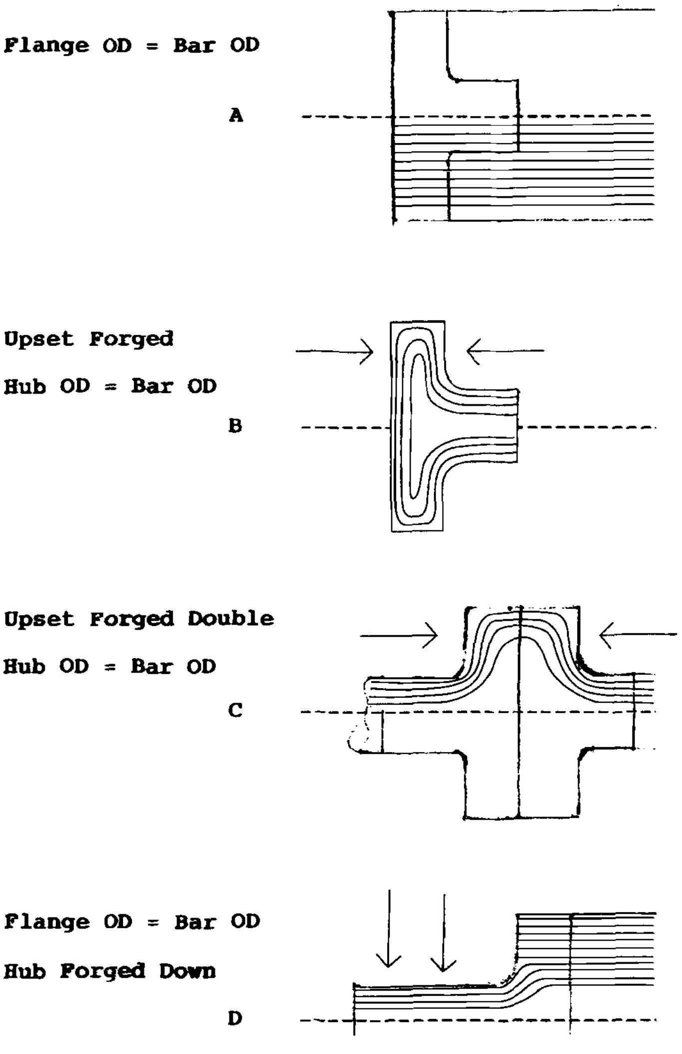

Fig. 14.1—Sketches of methods to produce flanges to an ASTM steel fittings specification using forged or rolled bar stock as the starting material: Method A, direct machining from bar is not permitted by the fitting specifications; Method B, by upsetting the flange from a starting bar size close to the flange hub size; Method C, by upsetting a double flange forging from bar close to the hub diameter; Method D, by starting with a bar size equal to the flange OD and forging the hub down. This may not be permissible by the fitting specification rules.

terial forms can be used within some defined limitations. The direct machining of rolled or forged bar material (note the definition from the terminology Section 3.1.1) is not permitted for flanges, so that the implication is that these components must be forged to shape. The exhortation to be as close as possible to the finished shape would seem to indicate that flanges should be forged individually rather than, for example, upset forged as a double and then cut apart. However, as Fig. 14.1 shows, this would seem to be a reasonable and economic way to make them. Another manufacturing route would be to select a bar with the same outside diameter as the flange and forge the bar down to make the flange hub, also shown in Fig. 13.1. This would certainly be close to the finished shape, but the flange would still be machined directly from the bar, and although having a favorable grain flow between the flange and the hub may not be in accordance with 6.1.1 of the specification. While the intent of these words may be clear, economics inevitably comes into the picture, and the restriction on directly machining flanges from any type of bar or seamless tube is much more meaningful.

Cylindrical parts, other than flanges, up to and including the NPS (Nominal Pipe Size) 4 can be machined from bar, but elbows, tees, header tees, and return bends cannot be machined directly from bar stock, regardless of the NPS size. The rule is that the longitudinal axis of the part must be near parallel to the axis of the bar, to avoid crossing the grain flow of the bar. There is no size limitation on cylindrical parts made from seamless pipe or tube, but the exclusion of flanges and nonaxial components such as tees and elbows still applies.

In common with other standards under the wing of Committee A1, Chemical Requirements (8) requires that Test Methods, Practices, and Terminology Standard A 751 be used for both heat and product analyses. It should be remembered that while in many cases the starting material for forging product standards covered by Specification A 961 will have been produced to specifications for other product forms such as hot finished bar and seamless tube, the requirements of A 961 would be expected to take precedence.

The Mechanical Requirements are shown in Section 9 and Specification A 370 is referenced as the test methods source. When the starting material is bar or tube whose heat treatment satisfies the requirements of the fittings specification, and when no heat treatments have been done after the mechanical testing of the stock, then mechanical test results from the starting stock can be used to satisfy the fitting specification requirements. While this is a useful provision for the manufacture of small parts, care should be taken to ensure that the heat treatment and mechanical test certification for the starting stock does really meet the particular fittings product specification requirements, since these are often quite specific with regard to temperatures and methods of cooling. Some words are also included concerning the manufacture and use of separate test blanks that are permitted in many of the product specifications. These separate test blanks can reduce mechanical testing costs appreciably, but have been a source of dissatisfaction in the past for forgings made to these product specifications when testing of an actual forging has been shown to give failing test results, although acceptable values were reported from the test blank. This is particularly the case when Charpy impact testing is required.

There is a common tendency for assorted forgings, other than for flanges, valves, and fittings for piping applications, to be made to the forged fittings product specifications. These applications frequently exceed the intended scope of the product specification test provisions with the potential for rejections and failures.

References

[1] *Annual Book of ASTM Standards*, Section 1, Iron and Steel Products, Volume 01.05, Steel Bar, Forgings, Bearing, Chain, Springs.

[2] *Annual Book of ASTM Standards*, Section 1, Iron and Steel Products, Volume 01.01, Steel Piping, Tubing, and Fittings.

15

Steel Forgings for the Fittings Industry

THE ASTM INTERNATIONAL STEEL FORGING STANDARDS for the fittings industry are all in dual format, so that forgings can be ordered to the customary English inch/pound units or to SI units. It should be noted that the size and weight of flanges, valves, and fittings for piping applications vary widely; a small threaded pipe coupling might weigh a few ounces (grams) while a valve body with integral flanges would weigh considerably more. The bulk of the standard pipe fittings probably rarely exceeds 1000 lb (454 kg) in weight, and even the very large special pipe fittings shown in Fig. 2.13 did not exceed 2 tons (1.8 t), but these were produced to a pressure vessel forging specification. The fittings specifications were written to cover the manufacture of relatively small standard parts such as flanges, elbows, tees, couplings, and valve bodies with maximum cross section sizes, probably not exceeding 4 in. (100 mm). The testing provisions were written to take these limitations into account and lend due economy to their production. It is this economy that opens some of these specifications to misapplication.

A mechanical testing provision common to many of the forged fittings specifications concerns using the same type of heat treatment at the same temperatures for austenitizing and tempering within a tolerance of ± 25°F (± 15°C). This reduces the tension testing frequency to one test per heat of steel, essentially a heat qualification test. This provision does not require the use of the same furnace, only the same temperatures. Significantly, cooling requirements are not included, and while probably not a concern for the intended fittings application, could be important for applications outside the scopes of the standards.

A 105/A105M-03, Carbon Steel Forgings for Piping Applications

This standard was published originally as a tentative specification in 1926 and has been in continuous use ever since. The heat treatment provisions of the specification and the simple mechanical test requirements have made it an attractive, but questionable vehicle for many carbon steel pressure vessel component applications, well beyond the scope range of flanges, fittings, and valves for piping applications. Earlier revisions to the scope clause, intended to reign in such applications, restricted use of the specification to forgings with a maximum weight of 10 000 lb (4540 kg). However, the scope clause does indicate that items such as tube sheets and cylindrical pressure vessel shells should not be manufactured to this specification.

The Heat Treatment section (5) is most important and should be read closely since the requirements depend on the type of component as well as the pressure and NPS designations. It is probably because of these provisions, more than any other, that misapplication of the specification has occurred. When heat treatment is required, there is a choice of annealing, normalizing, normalizing and tempering, or quenching and tempering. These operations are as laid down in Specification A 961. Heat treatment is *not* required for forgings falling under the following headings:

1. Standard design flanges for Class 300 or less from ASME Specification B.16.5.
2. Nonstandard flanges that do not exceed the temperature/pressure ratings for Class 300. Group 1.1 from ASME B.16.5.
3. Piping components (excluding flanges) exceeding Class 300 but not larger than NPS 4.
4. Piping components (excluding flanges) exceeding NPS 4 but not exceeding Class 300.
5. Piping components (excluding flanges) of Special Class (as defined in ASME B.16.34) that exceed Special Class 300, Group 1.1 working pressure at the design temperature, but do not exceed NPS 4.
6. Piping components (excluding flanges) of Special Class, exceeding NPS 4, but not exceeding the working pressure at the design temperature of Special Class 300, Group 1.1.

It will be seen that if the application restrictions listed in the scope clause and the heat treatment section are disregarded, then some quite large and thick forged components could be marked as complying with Specification A 105/A 105M without the need for heat treatment. An example could be a steel tube sheet some 6 ft (1.8 m) in diameter and 8.5 in. (215 mm) in thickness (weighing less than 10 000 lb (4540 kg)) that would be for service not exceeding Class 300.

Although for quenched and tempered forgings a $T \times \frac{1}{4}T$ tension test location is required, where T is the maximum heat treated section size, this type of heat treatment should not be necessary unless Charpy impact testing is a part of the purchase order; for example, through the use of Supplementary Requirement S54 from Specification A 961.

The Chemical Requirements section (6) and Table 1 deal with the permissible steel chemistry. Considerable attention has been paid to the chemical analysis requirements for carbon steel forgings over the years, since the specification was first published. Largely this has been due to the need to improve the weldability of the steel, and latterly to enhance toughness properties, although mandatory Charpy impact testing is not required by the Specification.

From an economic standpoint, there is also a need to be able to use the same steel supply for more than one specification application. This is particularly important for manufacturers that produce small forgings and who do not have their own melt shop for the supply of steel. The comparison of the chemical requirements from the 1955 revision of A 105 and the 2001 version of A 105/A 105M may be of interest:

Element %	1955	1985	2001	2003
Carbon (max)	[a]	0.35[1]	0.35[1]	0.35[1]
Manganese	0.90 max	0.60/1.05[1]	0.60/1/05[1]	0.60/1.05[1]
Phosphorus (max)	0.05	0.04	0.035	0.035
Sulfur (max)	0.05	0.050	0.040	0.040
Silicon	[b]	0.35 max	0.10/0.35	0.10/0.35
Copper (max)			0.40[2]	0.40[2]
Nickel (max)			0.40[2]	0.40[2]
Chromium (max)			0.30[2]	0.30[2]
Molybdenum (max)			0.12[2]	0.12[2]
Vanadium (max)			0.08	0.08
Niobium/Columbium (max)			0.02	

Note a: The carbon is restricted to 0.35 % if components are to be welded.

Note b: Silicon up to a maximum of 0.35 % may be required in order to meet the strength requirements when the carbon is restricted to 0.35 %.

Note 1: The maximum manganese level may be increased by 0.06 % for each decrease of 0.01 % in carbon below 0.35 %, up to a maximum of 1.35 % manganese (corresponding to 0.30 % maximum Carbon).

Note 2: The sum of chromium and molybdenum shall not exceed 0.32 %, and the total for copper, nickel, chromium, molybdenum, and vanadium shall not exceed 1.00 %.

It will be apparent that, although broadly similar to the 1995 revision, the chemical requirements of the current revision are rather more detailed and slanted towards consistent weldability and the potential for improved notch toughness. It should be noted that there is no restriction on how the alloying elements appear in the steel, either from the scrap or as alloying additions.

Section 7 on Mechanical Properties includes the minimum tension test requirements as well as the test location relative to the applied heat treatment, if any. Special provisions that exclude very small components produced on an automatic or semiautomatic press from tension testing are included in this section also. For these forgings, only hardness testing is required, and a hardness range is applicable. Another aspect that reflects making small parts from seamless tube is the provision for strip tension tests.

If the forgings are not heat treated, then only one tension test per heat of steel is required, regardless of the forging type or size or even when the forgings are made. No test location is specified for forgings that are not heat treated.

Originally, Specification A 105 offered two tensile strengths, Grade 1 at a minimum of 60 000 psi (415 MPa) and Grade 2 at 70 000 psi (485 MPa). The lower strength grade was dropped many years ago and with only one chemistry and strength level remaining, the grade designation was dropped also. The minimum yield strength is now 36 000 psi (250 MPa) and the minimum ductility requirement of 22 % elongation in 2 in. (50 mm) for the standard round tension test specimen is unchanged from the 1995 revision, as is the minimum reduction of area requirement of 30 %.

The longitudinal axis of the tension test specimen for heat treated forgings is required to be located at the $\frac{1}{4}T$ plane where T is the maximum heat treated thickness of the represented forging, and for quenched and tempered forgings there is the added location requirement that the midlength of the specimen is removed by a length T from any second surface. This is known generally as $T \times \frac{1}{4}T$ testing and an example is shown in Fig. 15.1. The use of a separate test blank taken from the heat used to make the forgings is permissible, and it must accompany a batch of the forgings it represents. Tension test orientation is not specified, but commonly in ASTM product specifications bars and forgings are tested with the longitudinal specimen axis parallel to the direction of hot working. This is termed longitudinal testing in Test Methods and Definitions A 370.

The Product Marking Section 13 could be confusing since part of the requirement (13.3) concerns certification for "larger forgings" when this is required. This again reflects a situation where, because of small forging size, the space available for marking is very limited. The section also addresses the addition of the suffix QT following the specification designation if the forging had been heat treated by quenching and tempering. An additional suffix W is required if the part had been weld repaired, with or without purchaser approval. Marking by bar coding is listed as being permissible.

In summary, while perfectly suitable for the pipe fittings for which it was written, Specification A 105/A 105M is open to question on its suitability for large forgings that are outside its scope.

A 181/A 181M-01, Carbon Steel Forgings for General Purpose Piping

This specification, originally published in 1935, is unique in that it covers nonstandard, as forged fittings, valve components and parts for general service. Like Specification A 105/A 105M, there is a weight limit of 10 000 lb (4540 kg), but unlike this specification there is no stated restriction on the application beyond forged fittings and valve components. Two classes are included, based on strength, but both share the same chemical composition requirements.

Under Materials and Manufacture (4) the same restrictions on machining parts from forged or rolled bar that are included in Specification A 105/A 105M are present. One useful feature is the provision for the manufacturer to supply a drawing of the proposed rough forging at the request of the purchaser. This could be important since it gives an idea of the amount of hot work going into the forging, and the potential grain flow in the part relative to the intended application. There is a requirement to protect the forging from thermal shock after forging.

The Mechanical Properties (6) requirements are found in Table 1, and this lists two classes. Class 60 is for a minimum tensile strength of 60 ksi (415 MPa) and a minimum yield strength of 30 ksi (205 MPa), and Class 70 requires a

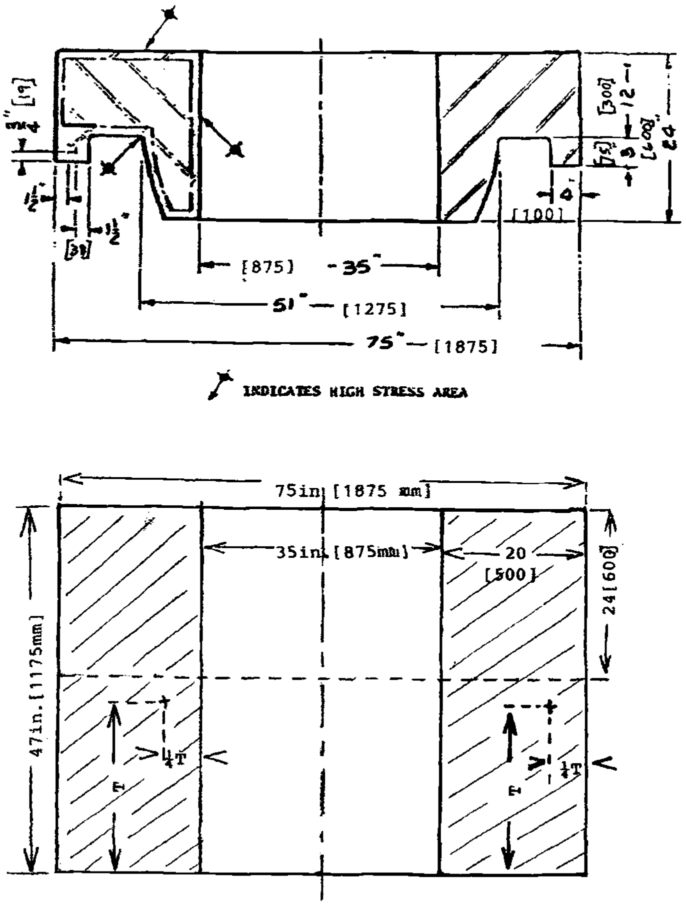

Fig. 15.1—For quenched and tempered forgings two test location systems are in common use. One is called *t* × 2*t* where *t* is the dimension between a designated highly stressed (in service) face of the finished forging and the closest quenched surface. However, *t* cannot be less than 0.75 in. (19 mm) even if the excess surface stock is less than this. The forging is contour machined prior to heat treatment as in this example. For the *T* × ¼*T* test location *T* is the maximum quenched cross section of the forging. In this example, the wall thickness of the forging would be *T* since heat is extracted from both the OD and ID surfaces. The ¼*T* location can be measured from the OD or ID surface at the manufacturer's option, unless otherwise instructed by the specification or the purchase order. Unless the quenched length is less than the wall thickness, as in a thick walled forged ring, the length is not considered in determining the *T* dimension.

minimum tensile strength of 70 ksi (485 MPa) with a minimum yield strength of 36 ksi (250 MPa). The reduction of area requirement for Class 70, at a minimum of 24 %, is lower than the already low value required in Specification A 105/A 105M, and reflects the coarser mixed microstructure structure that can be expected from as forged material.

A 182/A 182M-04, Forged or Rolled Alloy and Stainless Steel Pipe Flanges, Forged Fittings, and Valves and Parts for High Temperature Service

Again intended for small forgings, this is a widely used, and often abused, specification that is quite complex because of the wide range of materials that are included. These include alloy, ferritic, and austenitic stainless steels, and several duplex stainless steels. The application is for forged flanges, fittings, and valves made to specified dimensions or to dimensional standards. As in the case of the carbon steel forged fittings specifications, the use of forged or rolled bar is permitted with certain well-defined limitations. A size limit of 10 000 lb (4540 kg) is stated in the scope clause, but there is no exclusion for products such as tube sheets and pressure vessel shells. Specifications A 336/A 336M, Alloy Steel Forgings for Pressure and High-Temperature Parts, and A 965/A 965M, Steel Forgings, Austenitic for Pressure and High Temperature Parts, are cited for larger forgings or applications other than those related to piping applications.

Except for flanges, some cylindrically shaped parts can be machined directly from forged or rolled bar. Instead of the limitation used in Specification A 105/A 105M, reference is made to the fittings Specifications A 234/A 234M, Pipe Fittings of Wrought Carbon Steel and Alloy Steel for Moderate and High Temperature Service, for the ferritic materials, and A 403/A 403M, Wrought Austenitic Stainless Steel Piping Fittings, for the austenitic and duplex stainless steels, for the bar use restrictions.

Because of the wide range of included materials the heat treatments requirements in Section 6 are lengthy and are detailed in a table. This table includes minimum austenitizing and tempering temperatures for the ferritic steels and minimum solution treatment temperatures for the austenitic and duplex stainless steels.

Under mechanical testing for austenitic or duplex stainless steel forgings, there are no restrictions on the test specimen location, and only one test per heat is required regardless of forging or heat size, and time interval between heat treatment batches, provided that the test material was heat treated in accordance with the specification, with a production batch from the same heat. In other words a heat qualification process is used.

In the case of the alloy steels and both the ferritic and martensitic stainless steels, one tension test per heat is required from each heat treatment charge. As a departure from the requirements of Specification A 105/A 105M only like forgings, for example flanges, heat treated the same way, at the same temperatures can be accepted on the basis of one test from a heat.

Impact testing was not a part of Specification A 182/A 182M until the modified chromium-molybdenum (F 22V, F 3V, and F 3VCb) Grades were added. These were developed originally for petrochemical cracker vessel applications and Charpy impact testing was requested. This requirement is addressed in 8.7, rather than in a table. The required Charpy test temperature is 0°F (−18°C) with a minimum average absorbed energy of 40 ft-lbf (54 J).

Test reports must be supplied to the purchaser under the section (16) on Certification. This again contrasts with the current certification requirements of some other flange and fittings specifications.

A 350/A 350M-04a, Carbon and Low-Alloy Steel Forgings, Requiring Notch Toughness Testing for Piping Components

Although test methods for determining the notch toughness of steels were developed early in the last century, and Test Method E 23 for notched bar impact testing was published in 1933, it was not until the plight of the Liberty Ship brittle failures during World War II that the importance of notch toughness testing began to be widely understood.

Brittle failure is somewhat devastating because the ruptures occur extremely rapidly and can be catastrophic in extent—a ship breaking in two, or a welded pipeline rupturing longitudinally for a very long distance as examples—under loads that are well below the yield strength of the material. Several factors come into play when considering the risk of brittle failure:

1. The notch toughness of the material.
2. The design of the part.
3. The quality of manufacture.
4. The operating conditions.

It was found in the case of welded ship hulls that a horizontal strake of high toughness plate high above the water line, or for a pipeline the presence of a tough fitting such as a valve housing or a flange, could arrest a brittle fracture and exert a measure of damage control. This may have been the foundation for publishing Specification A 350 in 1953, and it is known that the American Petroleum Institute (API) [1] was very interested in the specification. When first published, Specification A 350 required the use of the Charpy keyhole specimen, so called because of the common method of producing the 5-mm-deep U-Notch by drilling a 2-mm diameter hole through the 10 × 10 mm section specimen and sawing from the face down to the hole to produce a 5-mm-deep notch with a 2-mm root radius. The U-Notch was discontinued in some North American specifications, such as the ASME Boiler and Pressure Vessel Code, about 40 years ago when the construction of nuclear power plants began, in favor of the more demanding 2-mm-deep V-Notch sample. This change, made without altering the minimum absorbed energy requirements or test temperature, was the basis for many of the subsequent material problems associated with Specification A 350/A 350M. The U-notch in various forms is still included in some European codes.

A characteristic of the Charpy impact test is scatter in the absorbed energy results, particularly when testing is done in the transition temperature regime for the material. For this reason a test consists of three specimens broken at the same temperature, and the result is the arithmetic average of the values obtained.

In discussing Specification A 350/A 350M, it should be noted that the scope section clearly states that the specification is for forged flanges, fittings, and valves for low temperature service, amplifying the specification title.

Two materials were available when Specification A 350 was first published, a carbon steel Grade LF1 with a minimum tensile strength of 60 000 psi (415 MPa) and Grade LF3, a 3.5 % nickel alloy steel with a minimum tensile strength of 70 000 psi (485 MPa). Currently, Specification A 350/A 350M includes seven carbon and alloy steel grades, and the minimum tensile strength requirements range from 60 ksi (415 MPa) to 75 ksi (515 MPa).

Specification A 350/A 350M is one of the most controversial of all of the ASTM steel product specifications in part because of some expensive installation problems that have been reported worldwide over a number of years. The general background on these difficulties will be discussed after the specification review.

The Scope clause describes the intended applications for the forgings for flanges, fittings, and valves to be made to special dimensional requirements or to dimensional standards that are listed in the specification.

Although the scope indicates that the specification is intended for pipe fitting, valve, and flanges for low temperature service, very large forgings for pressure vessel application have been ordered to it.

The accepted heat treatment cycles include normalizing, normalizing and tempering, or quenching and tempering, an exception being for the precipitation hardening Grade LF787. A minimum tempering temperature of 1100°F (590°C) is required, together with minimum holding times at temperature. An intercritical quench and temper cycle is also included. This procedure, while tending to reduce the tensile and yield strengths slightly, has been shown to enhance greatly notch toughness by means of significant grain refinement. It is useful in situations where a fine grain melting practice has not been used.

Special heat treatment requirements are needed for the precipitation hardening Grade LF787 and cooling from the austenitizing temperature may be done in air, as in a normalize or by quenching. The precipitation hardening stage is required to be done in the temperature range of 1000–1200°F (540–650°C) for normalized forgings and 1000–1250°F (540–665°C) for the quenched material.

The chemical composition section (6) refers to Specification A 961 and prohibits the use of leaded steels. Table 1 includes the composition limits for the seven grades. Probably the most widely used is Grade LF2. This is a carbon steel with the carbon limited to a maximum of 0.30 % and a manganese range of 0.60–1.35 %. At one time, the lower strength Grade LF1 had a more restricted manganese content, but with increasing heat sizes from the steel mills and the preference for steel stock holders to supply one composition for as many specification applications as possible, more standardized heat analyses have been requested. Aside from a fine grain size, toughness of the carbon steels is improved as the manganese to carbon ratio increases. A value of about 6 for this ratio can give good Charpy impact values. Limits on the residual alloying elements are included for all of the compositions, and detailed notes to Table 1 give added restrictions on the totals of certain of these elements.

The test temperature for the Charpy impact test has always presented difficulties both to those who order and those who produce forgings to this specification. The minimum absorbed energy value has more recently attracted attention. Originally, when the 5-mm Charpy U-Notch was specified, the test temperature for Grade LF1 was −50°F (−45°C) and 150°F (−100°C) for Grade LF3. The −50°F (−45°C) value was kept for Grade LF2 when that was introduced. When the specification was converted to the V-Notch specimen, the absorbed energy and test temperature requirements were unchanged. Although the remaining specimen cross section under the U-Notch is considerably less at 50 mm^2 compared with the 80 mm^2 under the V-Notch, the effect of the stress concentration difference between the two notches is such that, for a given steel and test temperature, higher absorbed energy values are obtained from the U-Notch. This effect was severe enough to make the difference between comfortably passing the minimum average of 15 ft·lbs (20 J) at −50°F (−45°C) for Grade LF2 and failing miserably. The basis for the choice of this test temperature (remembering that −40°F (−40°C) is the test temperature of choice for many military applications) for the specification is not clear, but may have been proposed by API [1] when the specification was first published.

Many applications require that impact testing be done at the lowest service temperature, and in Section VIII of the ASME Boiler and Pressure Vessel Code, −20°F (−29°C) is significant with regard to impact testing.

The average minimum absorbed energy value of 15 ft-lbf (20 J) for most of the materials in A 350/A 350M corresponds to a point approximately midway down the transition curve section between the upper and lower energy shelves.

At the present time Specification A 350/A 350M has approached the problem in several ways. The popular Grade LF2 now has two classes that vary in impact test temperature and absorbed energy requirements, and in addition Supplementary Requirement S1 permits the use of alternate purchaser specified test temperatures with a cap on the maximum temperature. When such alternate temperatures are used the marking of the forging must reflect this. In all, the test temperature and absorbed energy requirements are spread over three tables (Tables 3, 4, and S1.1.1) for the standard size specimen. These requirements are summarized in Table 15.1.

A key thing to remember in this test temperature item is that when using Supplementary Requirement S1, the actual test temperature used must be included in marking the forging.

A 522/A 522M-04, Forged or Rolled 8 and 9 % Nickel Alloy Steel Flanges, Fittings, Valves, and Parts for Low-Temperature Service

This specification was first published in 1964. It heralded a renewed specification writing activity by the subcommittee following the publication date of Specification A 350 some 12 years earlier. The 8 and 9 % nickel alloy steels met a requirement for materials with high toughness at cryogenic temperatures that could bridge the gap between the carbon and low alloy steels covered by the early version of Specification A 350, and the more expensive 300 series austenitic stainless steels that are also very useful at cryogenic temperatures. The ferritic nickel steels also have the advantage of having a higher yield strength than the austenitic stainless steels.

The specification Scope clause defines the operating temperature range for the materials as being from a maximum of 250°F (121°C) for both alloys, to a minimum of −320°F (−196°C) for the 9 % nickel steel and −275°F (−170°C) for the 8 % nickel steel. A further limitation is for a maximum heat-treated thickness of 3 in. (75 mm) for the double normalized and tempered condition and 5 in. (125 mm) for the quenched and tempered condition. These thickness limits, while quite conservative, are important because they are included as being mandatory in Part IID of the ASME Boiler and Pressure Vessel Code. Actual tests on 8-in.-thick (200-mm) forged 9 % nickel plate showed that all of the requirements of Specification A 522/A 522M could be met comfortably. This material was used for the forged fan drive shaft in a large cryogenic wind tunnel application in Langley, Virginia.

The specified heat treatments include the choice of quenching and tempering or double normalizing and tempering. The heat treatment requirements are unusual in specifying a minimum-cooling rate of 300°F (165°C) per hour from the tempering temperature, for both the normalized and quenched material. The recommended cycle for a post weld heat treatment includes a similar cooling rate. Both the 9 and 8 % Nickel alloys have the same minimum tensile strength requirement of 100 ksi (690 MPa), and instead of a required minimum average absorbed energy in the Charpy V-Notch test, the requirement is to obtain a lateral expansion of 0.015 in. (0.38 mm) at the test temperature of −320°F (−195°C) for the 9 % nickel steel or at −275°F (−170°C) in the case of the 8 % nickel alloy. This is in accordance with requirements of the ASME Boiler and Pressure Vessel Code (20).

The Mechanical Properties requirements are addressed in Section 7, and it should be noted that the lateral expansion requirements in the Charpy V-Notch impact test are not for an average value from three tests, but all three results must meet or exceed the 15 mils (0.015 in.) (0.38 mm) value. There is a concession that if one test from the set falls below the 15 mils value, but is not less than 10 mils (0.010 in.) (0.25 mm) and the average meets or exceeds the 15 mils (0.38 mm)

TABLE 15.1—Summary of the Charpy Impact Test Requirements for the Materials in A 350/A 350M

Grade	Class	Absorbed Energy Av. ft-lb (J) min	Test Temp. °F (°C)	Table S1.1.1 Max Temp. °F (°C)	Min. Tensile Strength ksi (MPa)
LF1	—	13 (18)	−20 (−29)	−10 (−23)	60 (415)
LF2	1	15 (20)	−50 (−45)	−35 (−37)	70 (485)
LF2	2	20 (27)	0 (−18)	—	70 (485)
LF3	—	15 (20)	−150 (101)	—	70 (485)
LF5	1	15 (20)	−75 (−59)	−60 (−50)	60 (415)
LF5	2	15 (20)	−75 (−59)	−60 (−50)	70 (485)
LF6	1	15 (20)	−60 (−50)	−40 (−40)	66 (455)
LF6	2	20 (27)	−60 (−50)	−40 (140)	75 (515)
LF6	3	20 (27)	0 (−18)	—	75 (515)
LF9	—	13 (18)	−100 (−73)	−80 (−62)	63 (435)
LF787	2	15 (20)	−75 (−59)	−60 (−51)	65 (450)
LF787	3	15 (20)	−100 (−73)	−80 (−62)	75 (515)

value, then a retest of three specimens is permitted. All three of the retest specimens must meet the minimum 15 mils lateral expansion requirement.

The test temperature of −320°F (−196°C) is the temperature of liquid nitrogen and is chosen for the 9 % nickel steel as a convenient cryogenic test temperature.

A 694/A 694M-00, Carbon and Alloy Steel Forgings for Pipe Flanges, Fittings, Valves, and Parts for High-Pressure Transmission Service

This specification was first published in 1974 to meet the needs of the steel transmission pipeline industry. In Section 5, Manufacture, the steel used is required to be fully killed, but the composition of the steels described as High Strength Low Alloy (HSLA) are broadly defined only in the Terminology Standard A941, Terminology Relating to Steel, Stainless Steel, Related Alloys, and Ferroalloys. The term "Alloy Steel" is used to describe only Grade L5 of Specification A 707/A 707M, Forged Carbon and Alloy Steel Flanges for Low-Temperature Service, but 6.3 of Section 6 on Chemical Composition must be read to disclose that. Reporting of a complete chemistry of the steel used is required. When HSLA steels are used, it is necessary for the manufacturer to report the chemical composition so that in this instance at least a partial test report is mandatory. Heat treatment is required and can be done by normalizing, normalizing and tempering, or quenching and tempering. The precipitation hardening temperature range given for Grade L5 of Specification A 707/A 707M is more restrictive than is required in that specification:

	A 694/A 694M Alloy Steel	A 707/A 707M Grade L5
Precipitation Range	1000 to 1225°F (540–665°C)	1000 to 1250°F (536–677°C)

In summary, Specification A 694/A 694M can be regarded as a vehicle for the use of proprietary HSLA steels for pipeline valves, flanges, and fittings for natural gas transmission service.

A 707/A 707M-02, Forged Carbon and Alloy Steel Flanges for Low Temperature Service

This standard was published shortly after Specification A 694/A 694M and also includes carbon and conventional alloy steels, as well as the precipitation hardening grade that is included in that specification. A feature of the specification is that it was written specifically for flanges. The scope section states that the forgings are intended for use in petroleum and natural gas pipelines in locations subject to low ambient temperatures. The writing of this specification fell into the time frame of the Alaskan oil pipeline. The scope also suggests the possible pairing of the different grades with the tensile strength classes, relative to the material section size capability. Grades L5, L6, and L8 are suggested as being suitable for any of the strength classes that range from 42 to 75 ksi (290–515 MPa) in yield strength.

The terminology section (3) includes two definitions, one being for *Flakes*, and the other for *Linear Surface Imperfections* (*Indications*). The latter definition of the linear indication length being at least three times its width is found in Test Methods A 275/A 275M, Magnetic Particle Examination of Steel Forgings Surface, and E 165, Liquid Penetrant Examination. Flakes (often referred to simply as flake) and discussed in Chapter 3 are fine internal ruptures or fissures that are associated with hydrogen in the steel.

Of all the flange and fittings specifications, A 707/A 707M is the only one to have a mandatory ultrasonic examination requirement for the weld neck area of flanges 24 in. (610 mm) and larger. This is required to be done to Practice A 388/A 388M, Ultrasonic Examination of Heavy Steel Forgings. An exception to Practice A 388/A 388M procedure, however, is that only a straight beam examination is required, whereas normally shear wave examination would be necessary, depending on the OD/ID ratio of the weld neck. Almost certainly flanges of this size would fall under the shear wave requirements of Practice A 388/A 388.

A 727/A 727M-00, Carbon Steel Forgings for Piping Components with Inherent Notch Toughness

This is one of the few Committee A01 product specifications that give an intended service temperature range, instead of the more general low or high temperature service notation. A temperature range of −20 to 650°F (−30 to −345°C) is mentioned in the scope. The advice is offered that, although notch toughness testing is not a requirement, inherent toughness can be expected. This expectation is based on heat treatment being a requirement regardless of the forging application, the required chemistry, and the limitation that the maximum *finished* section thickness cannot exceed 2 in. (50 mm). When impact testing is required the user is referred to Specification A 350/A 350M.

Three heat treatment options are specified in Section 5. These cover normalizing, normalizing and tempering, and quenching and tempering. Austenitizing temperature ranges are given depending on whether the forging is to be normalized or quenched, and a minimum subcritical tempering temperature of 1100°F (595°C) is required when tempering is performed. Another important heat treatment condition is that the forging must be allowed to transform after hot working before starting the heat treatment cycle.

The steel composition listed in Table 1 limits the carbon content to a maximum of 0.25 %, and the manganese range is 0.90–1.35 %. This permits a minimum manganese-to-carbon ratio of 3.6, and that could readily be adjusted to exceed 5. The higher manganese-to-carbon ratios tend to promote improved notch toughness. Nickel, chromium, molybdenum, copper, niobium (columbium), and vanadium can be added within the limits specified in Table 1 and the accompanying notes.

Under mechanical requirements the tensile strength range of 60–85 ksi (415–585 MPa) is specified in Table 2, with a minimum yield strength of 36 ksi (250 MPa). The cap on the tensile strength range is another factor that assists in maintaining impact properties. The use of a separate test forging or block is permitted but must represent the section thickness of the forgings in the charge within ± 0.25 in. (6 mm). Although not mentioned in Table 2, Tensile Requirements, it should be noted that a maximum hardness of 187 HB applies for every quenched and tempered forging. At first sight unnecessary when the tensile strength is capped, it should be remembered that under the specification rules very few forgings are actually tension tested.

A 836/A 836M-02, Specification for Titanium-Stabilized Carbon Steel Forgings for Glass-Lined Piping and Pressure Vessel Service

This specification is a good example of an ASTM standard written to meet the requirements of a specialized industrial process covering very specific applications and served by a small number of producers. Because of the application and the unusual heat treatment requirements, the components produced to this specification are all nonstandard in terms of dimensions, and importantly, the test specimens representing the forgings must receive simulated heat treatment cycles that represent the glass coating operations.

It should be noted that heat treatment of the forgings themselves is not required, but as mentioned earlier, the mechanical test material must receive the simulated glassing heat cycle.

The chemical composition requirements are included in Table 1, and reflect a mild steel with carbon restricted to a maximum of 0.20 % and a manganese maximum of 0.90 % together with the strong carbide forming element, titanium. The requirement for the latter is tied to the carbon content, with a minimum of four times the carbon percentage and a maximum of 1.00 %.

The modest tensile requirements are for a minimum tensile strength of 55 ksi (380 MPa) and a minimum yield strength of 24 ksi (175 MPa). These values reflect the repeated annealing cycles associated with the glass coating process.

Reference

[1] American Petroleum Institute, 1220 L Street, N.W., Washington, DC 20005.

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Forging Related Test Methods

SUBCOMMITTEE A01.06 ON STEEL FORGINGS AND billits has jurisdiction over some specific test methods and practices that are peculiar to forgings and that differ in some important respects from the hardness test methods and nondestructive examination standards that are the responsibility of other ASTM committees, such as E-28 on Mechanical Testing and E-7 on Nondestructive Examination. These special test methods and practices will be discussed first, before going on to look at the product specifications.

Magnetic Particle Examination

Two magnetic particle test methods are provided; one requires the use of d-c magnetization, and the other utilizes alternating current. These test methods do not include acceptance criteria; this generally falling within the scope of the product specifications; however, for forged crankshafts two specifications are provided that do include specific acceptance criteria and procedures. These will be discussed following the test methods.

A 275/A 275M-98, Test Method for the Magnetic Particle Examination of Steel Forgings

This standard was originally published in 1944 and reflected the need for looking at the magnetizing techniques and procedures for large, and often irregularly shaped, machined forgings, as opposed to relatively small diameter parts and bars that were later covered by Specifications E 109 and E 709. Magnetic particle flaw detection systems were widely used in industry, long prior to the original publication of Specification A 275, and they continue to be the most important surface examination method for ferromagnetic materials. The test method does not include acceptance criteria, but does give the basic requirements for a reproducible and reliable system that greatly increases the confidence level for surface integrity of the ferritic steels.

Because of its ability to permit the detection of near surface discontinuities, d-c magnetization is the basis for Test Method A 275/A 275M. It is permissible to use full or half wave rectified ac for magnetization. Reference is made to Specification E 1444, Practice for Magnetic Particle Examination, for minimum requirements, but it is made clear that in the case of conflict between the two standards, Method A 275/A 275M prevails. There is a reference to E 709, Guide for Magnetic Particle Examination, for the magnetic particle examination of forgings in the field. This would normally be expected for the re-examination of forgings after shipment and, perhaps because of some incident or rework, carried out away from the supplier's facilities.

The test method includes a short terminology section defining some terms that are used in the text. These include the definition of a *linear indication* as having a length at least three times its width, and *non-relevant indications* that are caused by conditions other than the presence of a potentially damaging flaw. Because they could be indicative of cracks or other stress risers linear indications are the primary target of the test method.

The competence of the operatives carrying out the test is obviously of paramount importance, and for this reason it is a requirement that the personnel are properly qualified. ASTM International does not offer this qualification function, but in North America the American Society for Nondestructive Testing (ASNT) [1] is accepted as having and maintaining an acceptable system for qualifying and certifying operatives for magnetic particle examination. Qualification to Recommended Practice SNT-TC-1A is required therefore for North America, but suitable qualification to some other national standard is permitted for other parts of the world. The object is that the operatives have shown competence by passing both written and practical tests.

Although by the use of d-c magnetization near surface indications can be revealed, it is a requirement that the magnetic particle examination be done after *all* thermal treatments, and in the final machined condition, or at least within 0.030 in. (0.80 mm) of the final surface. The importance of this may be lost on some users who regard the forging as received as semifinished and proceed to carry out additional machining, especially if the specified acceptance criteria are severe. In the event that this course is to be followed, it is important that agreement regarding liability be reached at the ordering stage.

The use of portable electromagnetic yokes is permissible, providing that the test sensitivity in detecting crack-like indications is maintained.

Often the magnetizing force is developed by the passage of current through the part, and it is important in this case that high electrical resistance is avoided at the contact areas in order to avoid burning or arcing effects that could be quite damaging in themselves. Woven copper tape made from wire is sometimes used to improve conductivity at the contact areas, but even then arcing and burning as shown in Fig. 11.2 must be avoided, since in addition to cracking this can lead to grain boundary penetration by copper. It is for this reason that the use of prods is not permitted in some product specifications, such as A 723/A 723M, that include high strength steels.

Surface preparation is addressed in Section 9, and this must be considered together with the sensitivity expected of the examination. If no indications are to be permitted in a particular location in the forging, as in the case of the critical area of a crankshaft bearing fillet, then the surface finish must be of a high order to assure that this goal can be demonstrated. Of course, in a highly stressed location such as this, an extremely fine surface finish is necessary for optimum fatigue strength, so that the requirements for the examination and for service are complimentary.

Freedom from grease or oils is essential because these materials can hold the magnetic powder if the dry method of application is used, and prevent wetting of the surface if the wet method is employed.

If the acceptance criteria are not too demanding, then shot blasted surfaces can be quite satisfactory, but loose scale would be a distinct hindrance and must be removed. A disadvantage of rough surface finishes is that they can readily give rise to false indications that can take up much time in assessment.

Section 10, Methods of Magnetization, is the heart of the test method and these are addressed in detail. Caution on the use of the *residual method* is expressed, and it is noted that purchaser approval is necessary before this method is used. Since some users may not have the expertise to understand its limitations, caution should be exercised in giving approval for the use of the residual method.

A key requirement for magnetic particle examination is that it must be done in two stages, with the direction of the lines of flux in the second stage being at right angles to the flux direction in the first stage. Methods for achieving this are described in some detail.

The field strength instructions are most important, and this is an area where differences may be found between Test Method A 275/A 275 and Guide E 709, Magnetic Particle Examination, and Practice E 1444, Magnetic Particle Examination. The magnetizing force current requirements for the latter standards are intended for small parts and can cause overheating and saturation when applied to large forgings. Requirements for both the wet and dry methods are covered. Generally, optimum sensitivity will be obtained by the use of the wet fluorescent method, in which the fine magnetic particles are coated with a material that will fluoresce under ultraviolet ("black") light. This method requires the use of a darkened environment, such as a special booth, and one needs to permit the eyes to become accustomed to the ambient light intensity. Requirements for the ultraviolet light intensity are included in the test method.

For most applications, particularly when dealing with large irregularly shaped parts, when the minimum flaw size is 1/16 in. (1.5 mm) or greater, the wet method under good shop lighting conditions is quite satisfactory. Requirements for the carrier liquid for the magnetic particles are included in the standard. A fairly high flash point is a most desirable characteristic.

It is sometimes useful to record the length and shape of the indication for a later report, and for this the build up of dry powder particles can be lifted off the surface by means of transparent tape and transferred to a white card. This technique enables an indication to be monitored, an example being shown in Fig. 11.5. For this purpose, when very fine indications are involved, suspending the particles in a volatile carrier such as methyl alcohol, and permitting the carrier liquid to evaporate can permit the indication trace to be lifted off. *Great care to avoid fire or harm from inhalation is necessary if such techniques are attempted.*

As mentioned previously, the test method does not include acceptance criteria, but does include a glossary of undesirable conditions that can be detected by the magnetic particle method.

The *Magnetic Particle Field Indicator*, sometimes referred to as a pie gage, is described in the test method. This simple but important instrument is invaluable in demonstrating that a sufficiently strong magnetic field has been set up during the examination.

Demagnetization is discussed in Section 12. Unless the forging is to be reaustenitized, this is an important follow-up to the examination, since residual magnetism in the part can be an embarrassment during later processing of the component or in service. For example, if the forging is to be part of a welded fabrication, residual magnetism can seriously and adversely affect the welding arc. Residual magnetism may be undesirable if the forging is in close proximity to sensitive electronic equipment, and would be very undesirable for a crankshaft because of a tendency to attract steel particles that could cause bearing damage.

A 966/A 966M-96, Magnetic Particle Examination of Steel Forgings Using Alternating Current

This is a companion test method to A 275/A 275M, but it utilizes magnetizing forces developed through the use of ac, instead of dc. The magnetizing effect is very shallow, so that only immediate surface indications are detectable. However, the forgings examined this way are very easy to demagnetize, so that residual magnetism problems are not a factor. For this reason, this method is favored for the magnetic particle examination of crankshafts. The method mirrors Test Method A 275/A 275M, and although the wet fluorescent method is often associated with it, A996/A 996M can be used for rough shot blasted surfaces of heat-treated forgings by the dry powder method when looking for processing defects such as quench cracks. Such forgings would be examined again after finish machining. To repeat, this method is used when residual magnetism problems, that can arise when a partially demagnetized regular shape is interrupted by a drilled hole or machined surface slot such as a keyway, would be objectionable. It should be noted, however, that residual magnetism in a rough heat-treated forging that has been shipped to another destination for machining could arise from handling by a crane electromagnet!

This test method was first published in 1996 and was written to provide the examination method for A 983/A 983M, Continuous Grain Flow Forged Carbon and Alloy Steel Crankshafts for Medium Speed Diesel Engines.

A 456/A 456M-99, Magnetic Particle Examination of Large Crankshaft Forgings

This specification was first published in 1964, referencing Test Method A 275/A 275M, and is actually an application standard for large slab (solid) forged crankshafts with bearing journals and crankpins of at least 8-in. (200-mm) diameter. Although this remains the principal application, this size limit was reduced to 4 in. (100 mm) minimum several years ago at the request of an engine builder. Three acceptance classes are currently provided, although as first published only the present Class 2 level was included.

A major change made after publication of Method A 966/A 966M was to switch to a-c magnetization in the interest of minimizing residual magnetism. Direct-current magnetization can still be specified by the use of a supplementary requirement.

Surface indications can arise from several different situations on the surface of a slab-forged crankshaft, and their significance has to take the operating conditions for the shaft into account. For this reason, magnetic particle indications are classified as being "open" or "non-open." An "open" indication is defined as being visible when the magnetic particles are removed, or one that is visible in a liquid penetrant examination. It follows then that if magnetic particle indications are found, then a liquid penetrant examination will probably be necessary. On a bearing journal surface, an open indication could result from a nonmetallic inclusion being dragged out of the surface during grinding or polishing. An indication of this kind, while perhaps not potentially troublesome from a crack propagation aspect because of its location, could cause tearing of a white metal bearing and subsequent severe bearing seizure. Remembering the potential for the ingot central segregation area to coincide with crankpin journal surfaces in slab forged crankshafts, the location and type of surface discontinuities becomes significant. This accounts for the need to investigate otherwise permissible surface indications in terms of length and number, by means of liquid penetrant examination to test for being open.

The parts of concern in a crankshaft for the specification are explained by sketches, and by the definitions of the major and minor critical areas in Section 6. Large areas of the crankpin webs are actually excluded from the acceptance criteria.

It should be noted that the least onerous acceptance criteria for the major critical areas are designated Class 1. Class 2 is more restrictive than Class 1 for both the major and minor critical areas, and Class 3 differs from Class 2 in that the requirements in the minor critical areas are tighter. Class 1 was introduced many years ago to meet a need for the supply of very large slab forged crankshafts for slow speed nondemanding applications where there was an economic problem in meeting the original requirements of Specification A 456. The steel supplier considered that there would be connotation of poor quality if the forgings were to be ordered as third class; hence, the increasing quality requirements with increasing class number!

It should be noted that this specification introduces the terms "depressing" and "dimpling." These have nothing to do with state of mind or smiling, but are connected with the actions to be taken to render a longitudinally oriented inclusion innocuous with regard to engine operation. The depressing operation is described in Section 8, Dimpling and Depressing, and is intended to preclude bearing damage. It should be noted that where depressing is required, it is not necessary to remove the indication. This work should be done gently and with great care to minimize bearing surface area loss. When dimpling is required, this too should be done with great care, and the periphery and bottom of the dimple should be smoothly rounded. In many cases, it is only necessary to reduce the length of the indication to an acceptable value rather than fully remove it. As a word of caution, the specification was written with an eye to the nonmetallic inclusions associated with ingot central segregation. Bearing in mind that the crankshaft was forged as a long rectangular slab, as shown in Fig. 2.15, and subsequently notched for crankpin location and hot twisted for orientation, there is a risk of nonaxial indications that might be from inclusions or tears from the twisting operation. These off axis indications can be very detrimental to crankshaft integrity and are addressed in the specification. Another risk, although rarer with widely used vacuum degassing, is the occurrence of hydrogen flake. These fissures can become exposed when the crankpins are machined and would be most deleterious. If sufficient time is permitted for the required incubation period, this type of defect should be found readily during an ultrasonic examination of the slab before notching for the crankpins.

Slab forged crankshafts are usually designed with parallel sided crankpin webs, and the axis of the main bearings and the crankshaft arms is offset from the axis of the original ingot. Another design, sometimes called a *barrel crankshaft*, has circular webs and is machined from a large cylindrical forging. Here the crankpins can be machined from the cylinder in their correct orientations so that no twisting is needed. The main bearing and arms of the crankshaft retain the ingot centerline axis, but the ingot centerline segregation problems can still exist in the critical areas of the crankpins, however. Efficient modern milling machines can remove large amounts of stock to a programmed profile, making this type of crankshaft economic to produce; however, continuous grain flow cannot be achieved by this production method.

A 986/A 986M, Magnetic Particle Examination of Continuous Grain Flow Crankshaft Forgings

This specification is intended to be used with the Product Specification A 983/A 983M for continuous grain flow crankshafts, and was first published in 1998. The test method for the specification is A 966/A 966M for magnetic particle examination using ac. The specification parallels Specification A 456/A 456M, but unlike that specification includes only one set of acceptance criteria, and is more restrictive in all respects. Another important difference is that only the wet fluorescent method of examination is permitted.

Ultrasonic Examination

Because of the variety of shapes and sizes in steel forgings, the requirements for their ultrasonic examination are more complex than is the case for regular shapes such as plate, tube, and pipe. Actual acceptance criteria are either specified in the product specification or by the purchaser.

A 388/A 388M-04, Ultrasonic Examination of Heavy Steel Forgings

This important standard practice is widely used for the examination of steel forgings and covers both longitudinal wave and shear wave scanning as appropriate for the particular geometry of the forging. The standard was written originally in 1955 when ultrasonic examination was in the early stages of use and is a required examination method in many of the forging product standards. As in the case of the magnetic particle examination standards, personnel qualification for North America is required to be in accordance with SNT-TC-1A [1], Supplement C—Ultrasonic Testing.

It is important to note that Practice A 388/A 388M is intended for use on ferritic steel forgings. Because of the sound attenuation problems associated with large coarse-grained austenitic stainless steel forgings, Practice A 745/A 745M, Ultrasonic Examination of Austenitic Steel Forgings, should be specified for their ultrasonic examination.

The intent is to achieve full volumetric examination of the forging after quality heat treatment, and either before or after any required stress relief. This requires machining of the forging to achieve the necessary degree of surface finish of at least 250 μin. (6 μm). Provision is made for the purchaser to amend this requirement in the inquiry or purchase order. For example, in the case of a closed die forging, heat-treated without machining, a scale free shot blasted surface might be permitted with purchaser approval. However, the same surface finish must be present on the calibration blocks.

The size and frequency of the search units is specified in Section 4 under the heading of Apparatus. The ultrasonic instrument requirements are outlined in Section 4 also, as well as details such as couplants and reference blocks. Engine lubricating oils are useful for coupling applications, but if heat treatment including stress relief follows the examination, these can cause unwelcome smoke, and water based gel couplants may be preferred. The sensitivity of the test improves with increasing search unit frequency, and 2.25 MHz is widely used. However, before quality heat treatment the forging grain size may cause base line noise and lower frequencies down to 1 MHz may be needed.

Depending on the forging geometry, it may be necessary to complete the ultrasonic examination in two stages, the first being full volumetric coverage before quality heat treatment, and the second to the maximum extent possible after heat treatment. Additional machining contours, over and above those needed to go directly from the forging to the finished shape, may be necessary to achieve this goal, and should be included in the *ultrasonic test procedure*. A written test procedure, complete with appropriate sketches, is often a useful tool for both the producer and the purchaser.

It is important to note that it is the contour of the finished forging that is the deciding factor in determining the extent of the ultrasonic examination. For example, a thick walled cylindrical forging may be made as a solid and bored afterwards. In this case, depending on the material, dimensions, and required mechanical properties, the quality heat treatment could be done before boring. By squaring the end faces and machining the surface, it may be possible to examine the forging simply by longitudinal wave scanning from the outside diameter (OD) and axially from the end faces. However, if after boring, the ratio of the OD to ID (inside diameter) is less than 2:1, then a shear wave examination as detailed in 7.3 of the Procedure section is necessary.

For the examination, it is important that the end faces of the forging have been machined square and those radii at changes in cross section are machined sharply to permit the maximum volumetric coverage. The radii size might have to be a compromise between full volumetric coverage and safety during heat treatment, or it may be necessary to recut the radii before heat treatment. All of this requires that the necessary machining stock on the forging be carefully evaluated at the time of designing the forging.

Calibration for the straight beam scan in its simplest terms can be based on the back reflection from a defect free portion of the forging, with recalibration necessary for areas where the thickness or diameter changes significantly. This is described in 7.2.2. The major problem with this method is that it is very difficult to judge the size of the reflector. Calibration using flat-bottom hole reference blocks is frequently used to improve on this, and the hole diameter becomes a significant factor. The hole size used rarely exceeds 0.25 in. (6 mm) and 0.125 in. (3 mm) is not uncommon for the calibration blocks. In some demanding application circumstances smaller calibration holes are required. Distance-amplitude correction curves are set up using several test blocks that represent set points in the cross section being examined; for example, at full thickness, ¾, ½, and ¼ thickness. Each of these would have the chosen flat-bottom hole size so that a calibration curve can be drawn on the instrument screen. Acceptance could be based on indications that cause reflections to cross the curve. This system allows for the location of the reflector in the cross section of the forging, and is described in Appendix X2.

The DGS (Distance-Gain-Size) calibration method is often used and this is described in Appendix X3 of the specification.

When a forging fails to meet the acceptance criteria, it may be necessary to excavate the questionable area to determine the exact nature of the indication, but sometimes the nature of the problem can be deduced from the number and location of the indications and the effect on the back reflection.

Shear wave examination is necessary for the axial scan (in both directions) of long pieces where longitudinal scans from both end faces are ineffective, as well as for the circumferential and axial scanning of hollow parts whose OD: ID ratio is less than 2:1.

Calibration for shear wave scanning is generally obtained by the use of OD and ID notches machined into an extension of the part, or in some instances into the part itself for later removal by machining or by repair. A notch depth of 3 % of the wall thickness up to a maximum of 0.25 in. (6 mm) and about 1 in. (25 mm) in length is specified in the standard. The notch shape may be square in section or as a 60° included angle V form, with the latter being preferred by most authorities, since it is harder to pick up. The shape of the notch used should be specified.

It should be remembered that geometric and in some cases microstructural features of the forging may give rise to reflections that are nonrelevant, and this aspect should be explored carefully if there is doubt.

Under the heading of Recording, instructions are given for making note of several situations that, unless otherwise agreed to, would not be considered to be unacceptable. These are noted for both longitudinal and shear wave examinations. Part of the reporting requirements is the preparation of a sketch to indicate where the recordable indications are located. Such information should be retained since it can be invaluable during any subsequent in-service examinations.

Although Practice A 388/A 388M is intended for essentially finished forgings, the need for early preliminary forging examinations is stressed, and the broad procedures of the practice can be applied, albeit that quality heat treatment has not been done, and the specified surface finish is not available. Such examinations can facilitate the salvage of a forging by means of careful layout such that objectionable indications can be removed during subsequent machining. At the worst a defective forging can be weeded out before adding further cost and delaying delivery. It is fairly common to do an ultrasonic scan of a forging immediately after the post forge handling stage, directly through adherent forging scale. Usually, this must be done with lower frequency transducers of 1 MHz or even 0.5 MHz because of the macrostructure and the scale. Protective diaphragms are needed to avoid transducer damage through contact with the scale, and sometimes it may be worthwhile to heat-treat the forging by normalizing to refine the structure and lessen attenuation if there is doubt about a potentially troublesome indication. It is often possible to change an open die forging layout to skirt ultrasonic indications that have been revealed by preliminary examination. Although largely a matter of economics and common sense, the early stage ultrasonic examination does constitute a manufacturing cost but is something to be considered seriously, and it can point to a need for additional process control elsewhere in the operation.

Suggestions for how quality levels can be specified are included for both compression and shear wave examinations.

A 745/A 745M-94, Ultrasonic Examination of Austenitic Steel Forgings

This standard practice was first published in 1977 and is intended to address the particular limitations found in the ultrasonic examination of austenitic stainless steel forgings. The standard parallels Practice A 388/A 388M, but one of the major differences is that although 2.25 MHz is the preferred transducer frequency, it is recognized that many examinations will be done at 1 MHz because of attenuation effects caused by the coarse grain size. The use of search unit frequencies as low as 0.5 MHz is permissible, but the purchaser can request notification of such a move. Heat treatment of austenitic stainless steel forgings consists of solution annealing, and this must be completed before the ultrasonic examination is done. A written test procedure is required for the test if full volumetric examination is not possible in a contour forged part. Axial scanning by longitudinal wave from both ends is required when the axial length exceeds 24 in. (600 mm), or when the length divided by the diameter ratio exceeds 6:1. An axial shear wave scan from the OD surface is an acceptable alternate. The use of reference block material that has approximately the same attenuation characteristics as the forging is strongly recommended.

Another important difference between the two practices is that for the convenience of the purchaser Practice A 745/A 745M provides Quality Levels for Acceptance in Section 12.

For compression wave (straight beam) scanning, five quality levels are provided:

- QL-1: No. 8 flat-bottom hole ($^{8}/_{64}$ in.) or (3 mm) (Practical for T up to 3 in. (75 mm))
- QL-2: No. 16 flat-bottom hole ($^{16}/_{64}$ in.) or (6 mm) (For T up to 8 in. (200 mm))
- QL-3: No.24 flat-bottom hole ($^{24}/_{64}$ in.) or (10 mm) (For T up to 12 in. (300 mm))
- QL-4: No. 32 flat-bottom hole ($^{32}/_{64}$ in.) or (13 mm) (for T up to 24 in. (600 mm))
- QL-5: Freedom from complete loss of back reflection (less than 5 % of full screen height) accompanied by a discontinuity indication. (Practical for T over 24 in. (600 mm))

For shear wave scanning, the following levels apply:

- QA-1: Acceptance based on a notch equal to 3 % of the examined thickness.
- QA-2: Acceptance based on the lesser of a notch at 5 % of the thickness or 0.75 in. (19 mm).

The quality levels are essentially suggestions, and the purchaser can specify other acceptance criteria.

A 418-99, Ultrasonic Examination of Turbine and Generator Steel Rotor Forgings

This test method was first published in 1957 and generally is either used directly by steam turbine and generator builders, or is incorporated into private specifications. The test method is specifically directed towards cylindrical solid or bored forgings typical of turbine and generator rotors, and does not reference Practice A 388/A 388M. The emphasis is heavily weighted toward reflector size, and attention is directed towards the equipment to be used in the examination. The examination must be performed on parallel-sided cylindrical shapes, and if conical forms are a part of the final machined form, then these must initially be made and machined as cylinders for at least the initial examination, if necessary, before quality heat treatment. This situation must be reflected in forging drawings and scanning sketches. Frequently this type of examination is performed with the rotor set up in a lathe or on rollers to permit slow rotation as the scanning operation continues. An appendix (XI) gives details of how the sensitivity multiplication factors are determined.

A 503/A 503M, Ultrasonic Examination of Forged Crankshafts

This specification, currently in dual format, was first published in 1964 and was intended for application to large slab or barrel forged crankshafts (referred to as *Solid Forged* in the standard) for low-speed diesel engines and gas compressors. The scope was originally written to include crankshaft bearing and pin diameters of 8 in. (200 mm) or greater, but was extended to cover crankshafts, both solid and continuous grain flow, with journal diameters of 4 in. (100 mm) and larger. Practice A 388/A 388M is the reference method.

Excluding the slab or solid forged crankshafts that begin as fairly simple shapes, crankshaft forgings are, by design, irregularly shaped, and consequently, present difficulties for ultrasonic examination. After notching for the crankpins and subsequent twisting to the correct angular orientation (normally followed by quality heat treatment), the slab forged shafts present similar problems. Since the crankshaft must include integral provision for bearing lubrication, it is necessary for an ultrasonic examination to be done prior to drilling oil passages. By the same token it is necessary to machine tapers and keyways after completing the ultrasonic examination.

The specification includes acceptance criteria based on the locations of the stresses imposed on the crankshaft during operation. For this purpose, the shaft is divided into three zones with Zone 1 being the most critical and Zone 3 the least. Unless Supplementary Requirement S1 for reference block calibration, or S2 for the use of DGS scales has been specified, acceptance is based on reflector indications rated against the back reflection calibration. The procedure used depends on whether the crankshaft was produced by slab (solid) forging or by the continuous grain flow method.

For continuous grain flow crankshafts, the shape makes full volumetric examination very difficult, but significant areas can still be examined provided that reflections from geometric sources are taken into account.

A 531/A 531M-91, Ultrasonic Examination of Turbine-Generator Steel Retaining Rings

This is a stand-alone practice for the ultrasonic examination of a very specific forged product used in the assembly of turbine and generator rotors. The practice includes both contact and immersion scanning methods. The ring materials may tend to be coarse grained; however, if this condition interferes to the extent that calibration from the test notch is impaired, then the ring may be rejected. The purchaser is required to supply details on how the examination is to be conducted. In common with other turbine and generator component specifications, final disposition of rings that have been found to contain reportable conditions rests with the purchaser.

A 939-96, Ultrasonic Examination from Bored Surfaces of Cylindrical Forgings

This standard was first published in 1995, and is unique among ASTM nondestructive test methods in having no reference standards. The method, intended for the examination of turbine and generator rotor forgings, uses small dual longitudinal wave search units of a specific size, and unless otherwise required, a frequency of 2.25 MHz. The purchaser is expected to supply the calibration hole size, and the method is applicable to bore sizes down to 2.5 in. (64 mm). The test procedure, including the use of the dual transducer search unit, is not described in great detail. Reporting information is included in the standard and the purchaser is responsible for specifying acceptance.

General Comments

Automated ultrasonic examination systems have been developed for specific forged components such as rotors, wheels, and disks, but none of these have been proposed as yet for inclusion in an ASTM standard. Some examples were included in papers [2–4] that were presented at the 14th International Forgemasters Meeting in Wiesbaden, Germany in September 2000.

Portable Hardness Testing Standards

Hardness of steel is a useful engineering property that is related to tensile strength. Although it tells nothing of yield strength and ductility, it is helpful as a means of demonstrating that a part probably has been heat-treated in accordance with the specification. Because of the relationship to tensile strength, hardness is sometimes used in some product specifications to impose upper limits on tensile strength, and in some instances when tension testing is limited, for example, to one tensile specimen from a furnace batch of forgings, hardness testing can give some assurance that heat treatment was uniform.

Although used in many steel product form specifications, hardness testing is particularly important for forgings and castings because of their size, and configuration considerations.

The two common hardness-testing classifications used in ASTM steel forging standards can be described as *Indentation* and *Rebound* methods. Of these the rebound hardness system is specified in only one product standard, A 427, Wrought Alloy Steel Rolls for Cold and Hot Reduction, although this hardness testing method is widely used to test other forged products.

Hardness testing of forgings using the standard indentation bench hardness testers often can present difficulties because of size and shape considerations, and this spurred the development of portable hardness testers.

Brinell hardness, besides being the oldest, is probably the most common of the hardness scales used in engineering worldwide, and is the one most frequently specified in Committee A01 specifications. The basic Brinell system is described in ASTM Test Method E 10, Brinell Hardness of Metallic Materials. Currently, Test Method E 10 requires only the use of a tungsten carbide ball, mainly because of the effects of surface wear in steel ball indenters. It should be noted that tungsten carbide balls have been available for the Brinell test for many years; they are mentioned in the 1954 revision of Test Methods and Definitions, A 370, and have been in wide industrial use since then.

The rebound systems such as the Scleroscope (Practice E 448, Scleroscope Hardness Testing of Metallic Materials) and Test Method A 956, Leeb Hardness Testing of Steel Products, are dynamic tests and they measure the rebound height of a tup dropped onto the prepared test surface. This measurement is related to the elastic modulus of the steel, and so to its hardness.

Attention is drawn to a most useful ASTM standard, E 140, Hardness Conversion Tables for Metals. For convenience, this is quoted in A 370, Mechanical Testing of Steel Products.

The subject of hardness testing of steels is quite complex and should be approached with caution, with great care being taken to report the results together with the necessary references for the test method used. This is particularly important when portable hardness testing methods are used. Unfortunately, hardness values are often reported without these references.

A 833, Indentation Hardness of Metallic Materials by Comparison Hardness Testers

This practice was first published in 1984 and continues in its original form with successive reapprovals as required by the ASTM regulations. The standard is intended to address the use of certain commercially available hardness testing equipment typically called *Hammer Brinell Testers*. This type of equipment is used for hardness testing of large components, typically forgings or castings that are too large to fit under a Brinell hardness tester. Several commercial variants using the comparison Brinell indentation system have been produced. These typically use a steel housing similar to a punch fitted with a replaceable 10-mm-diameter hardened steel or carbide ball at one end. Provision is made in the body of the punch for a rectangular steel test bar to fit diametrically above, and in contact with the ball. The punch is held onto the prepared workpiece surface and is struck a single blow sharply by a hammer. The ball simultaneously makes an impression in the test bar and the workpiece. The diameters of the impressions are measured using a standard Brinell measuring microscope, and the workpiece hardness is obtained from tables supplied by the equipment manufacturer, or is calculated from the equation given in the standard. Care must be taken to ensure that the punch is only struck once, and that the blow was not severe enough to cause side bulging of the test bar. Obviously the test bar itself is a vital link in the test, and for best accuracy, it is recommended that the hardness of the test bar should approximate that of the forging within a range of about 30 Brinell points. It is apparent then that a suitable selection of test bars in appropriate hardness values should be available.

It should be noted that hardness testers using shear pins to determine the applied load are not covered by Practice A 833.

A 956-02, Leeb Hardness Testing of Steel Products

This test method was first published in 1997 as A 956-97, Equotip Hardness Testing of Steel Products. This instrumented portable rebound hardness test was first published under the patented name, Equotip, but when several other manufacturers' devices entered the market following expiration of the patent, the title of the standard was changed by ballot action to reflect the name of the inventor of the method, Mr. D. Leeb, following the example of the Brinell, Vickers, and Rockwell tests. This is a widely used hardness test method, at least in the foundry and forging industries, and also for work in the field. Since this is a rebound hardness test, conversion of the Leeb hardness numbers obtained from the test to conventional numbers like Brinell, Vickers, or Rockwell C scale is difficult, and such conversions are not currently included in the E 140 standard, although this is expected to be accomplished. The equipment manufacturers, however, do provide such conversions for their own instruments and frequently the results can be read from the instrument using built-in conversions. This is permitted by the test method. The equipment is compact and readily portable as shown in Fig. 16.1. Because of the nature of the test, it should only be used on substantial sections. The standard test blocks must be at least 3.5 in. (90 mm) in diameter and 2.125 in. (54 mm) thick for most of the impact devices used, and in some cases, up to 4.75 in. (120 mm) in diameter and 2.75 in. (70 mm) thick. Depending on the instrument used,

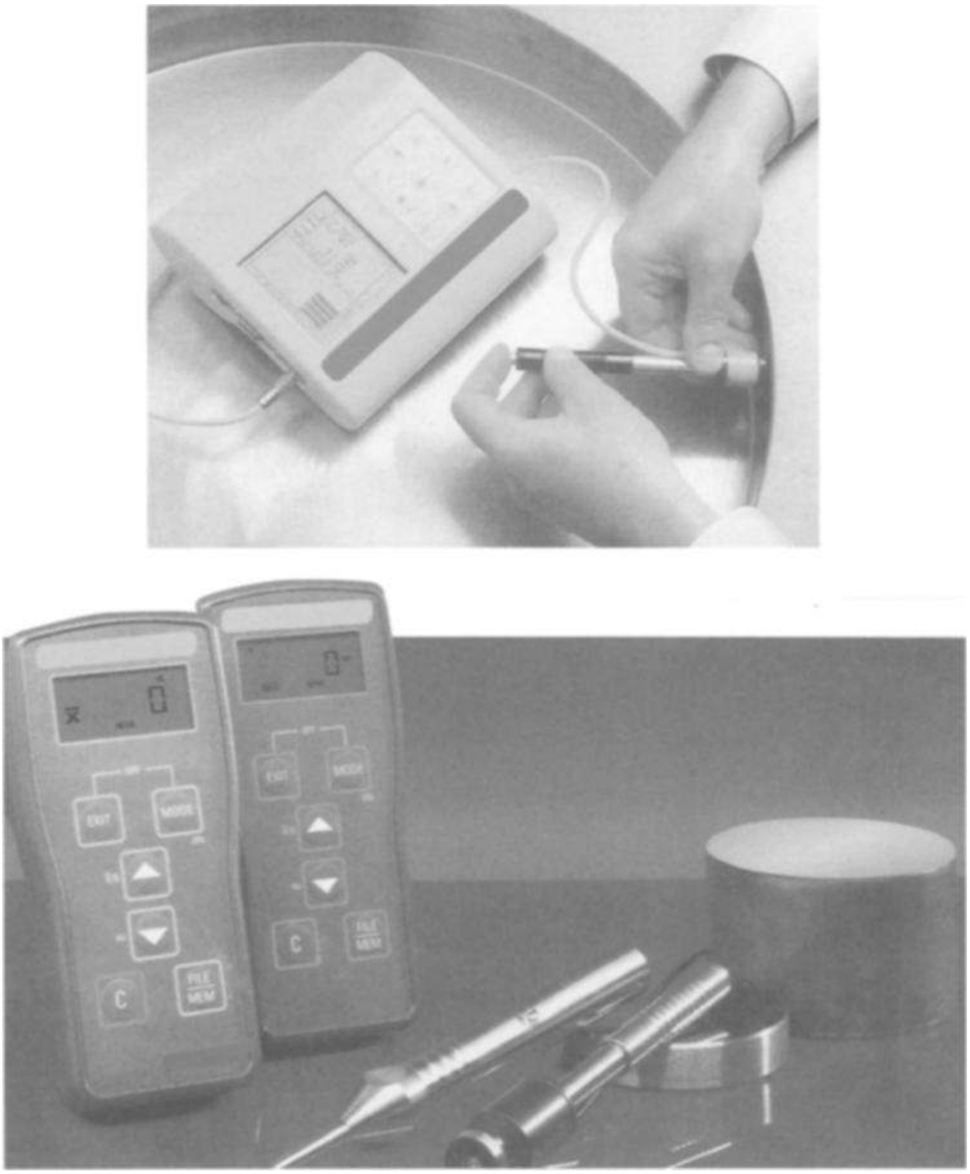

Fig. 16.1—Examples of commercial Leeb hardness testers. They are typically very portable and normally include built-in conversion to conventional hardness scales as derived by the equipment manufacturer. Note the thickness of the hardness test block in the lower picture. (Courtesy of Proceq SA (top) and GE Inspection Technologies (bottom))

it may be necessary to apply a correction factor for instrument orientations that are not vertical.

Other Portable Hardness Testing Methods

An assortment of portable hardness testing equipment for Brinell, Vickers, and Rockwell C and B scales has been available for many years. Generally all have advantages and limitations, and use may not be possible in all situations. In some instances such equipment is permanently mounted on machine tools, such as radial arm drilling machines, but care has to be taken to ensure that inherent flexibility in the support equipment does not detract from the applied hardness test load resulting in inaccurate readings. This is particularly true if the machine used to support the hardness tester was retired from its original duties because of wear problems!

A new standard practice A 1038-05, Portable Hardness Testing by the Ultrasonic Contact Impedance Method, was published early in 2005.

Heat Stability Testing

A 472-98, Heat Stability of Steam Turbine Shafts and Rotor Forgings

This specification was first published in 1962 and is an example of a special test method intended for a specific industrial purpose. When a rotor forging for a steam turbine is made, a number of forging steps are involved, and it is important that the longitudinal axis of the original ingot is maintained as the axis of the rotor forging. This alignment could be lost at the outset, for example, if the ingot was to be stripped early from the mold before solidification was complete, and laid on its side. If the ingot had been stripped from the mold properly, but had been heated unevenly for forging such that there was an appreciable temperature differential from side to side, then during forging, because of unequal metal flow, the ingot axis could be shifted away from the axis of the forging. This is often called being cold sided. Chemical segregation is associated with the ingot axis and is generally symmetrical around it, and although there are other segregation effects from top to bottom of the ingot, these too are generally symmetrical around the longitudinal axis. When the ingot axis is displaced from the forging axis, the chemistry imbalance may be sufficient to cause the rotor forging to bow when it is heated because of unequal expansion from side to side. This could cause the turbine blades to rub against the steam chest. When cold, the rotor would return to the straight condition. This would represent an unsatisfactory permanent situation. Another source of rotor bowing at temperature is residual stress in the forging, perhaps from heat treatment, subsequent machining, or straightening. This condition is temporary and can be cured by a stress relieving treatment. Sometimes stress relief and the heat stability test can be combined into one operation.

The heat indication test is carried out in a special furnace large enough to contain the parts of the rotor body that are required to be tested, as illustrated in Fig. 16.2, and which will permit the rotor to be rotated slowly while being heated and during the hold period at the required temperature (given by the purchaser) and during subsequent cooling. Often an old lathe provides the basis for the equipment. Datum points on the OD of the rotor are specified by the purchaser and control rods connected to dial gages contact these areas through the wall of the furnace.

The procedure is properly explained in the standard, together with details of the necessary information to be supplied by the purchaser and the test result reporting. Although intended for turbine rotor forgings, this test method could be used for a fanshaft designed for use at elevated temperatures.

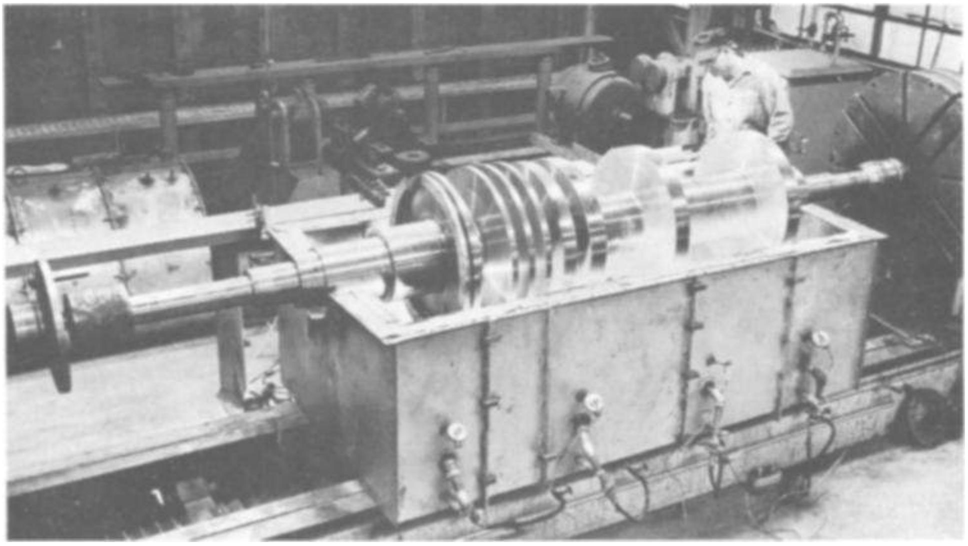

Fig. 16.2—An example of a heat indicating lathe with a steam turbine rotor forging installed. When the upper cover of the furnace is installed the rotor can be brought up to the required temperature while rotating. Indicator rods inserted through the furnace wall touch the rotor at designated points and their deflection is recorded during the period of the test. (Courtesy Ellwood National Forge Company)

Macro Structure Tests

A 604-93, Macroetch Testing of Consumable Electrode Remelted Steel Bars and Billets

This test method was first published in 1970 and was revised in 1977 and 1993. It is a companion standard to ASTM E 381, Method of Macroetch Testing Steel Bars, Billets, Blooms, and Forgings. The latter method is applicable to hot worked steel produced from ingots or from strand casting, where the solidification effects differ significantly from those of remelted ingots.

The test method was written because of the special conditions that could be found in vacuum arc remelted (VAR) ingots that could affect forging quality. When the electroslag remelting (ESR) process became of interest for forging stock, requirements for these ingots were added.

As is the case with Method E 381, those using Method A 604 should obtain the adjunct sheets (ADJA 0604) that show the full set of 20 reference macrographs in much better detail than is possible in the published book of standards. These can be framed and made readily available for the laboratory staff. It is important to note that the macrographs are considered to be applicable to billet or bar cross-sectional areas up to 225 in.^{2} (1400 cm^2), that is 15 in. (375 mm) square or about 17 in. (425 mm) in diameter. This would be about the size, after a forging reduction of 3:1 of a billet or bar from a 30 in. (750 mm) remelted ingot. Much larger remelted ingots are available, particularly in the ESR process. The acceptance ratings for larger sections must be agreed upon between the purchaser and supplier. This may be a three-way decision since the forging supplier may have to purchase the remelted material.

A further point to consider is that in the published standard the macrographs have been reduced by 44 % (9.3) so that the 3.375-in. (85-mm) sections were originally 7.625 in. (190 mm) across. Since the actual test section is being examined by eye at full size, this reduction must be taken into account in assessing the macro.

For those unfamiliar with the VAR and ESR processes, the nonmandatory appendices include useful descriptions.

References

[1] Wieser, R. and Koppensteiner, R., "GFM Radial Forging Design Development," *The 14th International Forgemasters Meeting*, Wiesbaden, Germany, October 2000, pp. 145–150.

[2] Finali, A., Borgna, R., and Leupoldt, K., "Innovative Mechanized Inspection Technique Replaces Manual Inspection of Heavy Forged Rotors," *14th Annual Forgemasters Meeting*, Wiesbaden, Germany, September 2000, pp. 426–428.

[3] Escher, K., Stein, G., and Gripp, S., "Automated Ultrasonic Surface and Volume Testing of Contoured Discs," *14th Annual Forgemasters Meeting*, Wiesbaden, Germany, September 2000, pp. 429–434.

[4] Pfeiler, H., Zeiler, G., and Bauer, R., "First Experiences in Testing Heavy Forgings with an Advanced Automatic Ultrasonic Testing Facility," *14th Annual Forgemasters Meeting*, Wiesbaden, Germany, September 2000, pp. 435–439.

17

Steel Forgings for the Pressure Vessel Industry, other than for Fittings, Flanges, and Piping Application

THIS GROUP OF SPECIFICATIONS WAS WRITTEN TO address forgings for large pressure retaining components, whose weight would normally be measured in tons rather than pounds, and where a wall thickness of 1 in. (25 mm) would be considered to be thin. As a consequence, the heat treatment and testing requirements both mechanical and nondestructive are more demanding than those found in the piping fittings standards.

A 266/A 266M-03, Carbon Steel Forgings for Pressure Vessel Components

First published in 1943, this specification was written to meet requirements for the drums of water tube boilers and other forged carbon steel pressure vessels. The original title was Carbon Steel Seamless Drum Forgings. In the early water tube boiler designs, the drums were of riveted construction from steel plate rolled to form the shell. The longitudinal riveted seams utilized internal and external double riveted butt-strap construction, and the circumferential seams were lap riveted. This method of construction limited plate thickness and, hence, the operating boiler pressure. The use of monoblock fully forged steam and water drums offered a means of increasing steam pressure with the attendant efficiency improvements. One piece forged boiler drums could be produced to A 266 in one of three carbon steel classes that ranged in minimum tensile strengths from 60 000 psi (415 MPa) to 75 000 psi (515 MPa). The drums could be hollow forged on a mandrel to obtain the required OD and ID diameters and length before closing-in operations by forging to form the end caps or heads. The manholes could be conveniently located in the heads along the axis of the forging. The tubes were expanded into the holes drilled in rows along the length of the drum. This type of construction essentially precluded the need for welding, other perhaps than some seal welds, and accounts for the fairly high carbon content (0.50 % max.) permitted for the original Class III material. On the subject of chemical composition, it is of interest to note that when first published allowance was made in the phosphorous content for the method of steel making used. For acid open-hearth steel, a maximum phosphorous limit of 0.05 % was imposed, but if basic open-hearth steel was available, the phosphorous limit was reduced to 0.04 %. For service applications above 800°F (425°C), a supplementary requirement for coarse-grained steel between ASTM ratings 1 and 5 was available. Notch toughness requirements were not imposed, and such forgings gave reliable service for many years.

Today Specification A 266/A 266M includes four grades of carbon steel, two of which share the same tensile strength properties, and all are considered to be suitable for welded construction under the rules of the ASME Boiler and Pressure Vessel Code [1]. The change from Class to Grade designation was made in accordance with Committee A01 policy, and the original notations are shown in the scope clause of the specification for the assistance of those who may wish to replace components made to old drawings.

The General Requirements Specification A 788 is an important part of Specification A 266/A 266M, in common with most of the specifications under the jurisdiction of Subcommittee A01.06, and the importance of using both documents when ordering or making forgings should be recognized.

It is anticipated that forgings made to this specification will be machined, but there is a notation in Section 5, Machining, that surface scale must not interfere with inspection of the forging. This probably dates from the days of the one piece forged boiler drums. It is further recognized that machining before heat treatment may be necessary, and unless Supplementary Requirement S1 is included in the purchase order, this is left for the manufacturer to decide. Machining before heat treatment has the advantage of removing excess stock, particularly if open die forging is involved. Excess material thickness will increase furnace hold times, and therefore cost, and as a general rule reduced section thickness improves heat treatment response and mechanical properties. Cost increase because of extra machining setups is a potential offsetting disadvantage. Heat Treatment, Section 6, is mandatory, and the forging must be permitted to transform after completion of the forging operation before starting the quality heat treatment cycle. Annealing is listed as a heat treatment option, and it should be noted that subcritical annealing is not included in this term. Purchaser agreement is necessary if quenching and tempering is to be performed. Tempering is required to be done at a minimum of 1100°F (595°C). The intercritical quench and temper heat treatment procedure is permitted in 6.3. Although increasing heat treatment cost by the introduction of an additional furnace heating stage, this treatment is effective in improving notch toughness by causing significant grain refinement. Note 2 to 6.3 makes the point that, although not as effective as intercritical quenching in improving Charpy impact values, intercritical normalizing does give an appreciable improvement in transition temperature through significant grain refinement [2]. This type of treatment is helpful for steels with low manganese to carbon ratios.

The Chemical Requirements are similar to those of Specifications A 105/A 105M and A 350/A 350M for Grades LF1 and LF2, but restrictions on the residual alloying elements are not imposed. The purchaser can specify Supplementary Requirement S11 for this purpose, as well as S1, S2, S10, and S11 in the General Requirements Specification A 788. In addition, Supplementary Requirement S15 can be used to impose a carbon equivalency limit for the steel. When large heavy section forgings are required, the carbon equivalency option should be discussed carefully with the forging supplier. Since certification is mandatory, this approach permits the purchaser and producer to arrive at an equitable compromise.

The Mechanical Properties Section 9 gives the tension test requirements for the four steel grades in Table 2. The minimum yield strengths are approximately half of the tensile strength, so that in many cases an annealing heat treatment will achieve the required minimum properties. However, impact properties tend to be poor after annealing, and Charpy testing may be an application code requirement. Tension test locations are described for various shapes such as upset disks and cylinders. In most cases, the tests are required to be taken from the midradius or quarter wall thickness location, but the exception is for tests taken from the periphery of upset disk forgings when the tests are to be located at midthickness. In terms of test orientation the object is for the tests to be taken parallel to the direction of maximum forging work. For an upset disk forging this orientation is taken to be tangential to the periphery of the forging, and for a solid forging parallel to the longitudinal axis. For a hollow cylindrical forging, depending on the actual practice used, the orientation could be tangential to the OD or parallel to the axis. Supplementary Requirement S2 requires that the tension test specimens be taken transverse to the direction of maximum work, and revised ductility values included in the supplement are then applicable. As a throw back to the integral drum forgings described earlier, special heat treatment and testing requirements apply as described in 8.1.2. Separately forged test bars are permitted as described in 8.1.3. These are useful for large forged rings where length restrictions preclude the integral test prolongations that are intended for forgings made to this specification. A warning about the unfavorable mass effect difference between a large forging and a separate test bar is included in the text. The heat-treated forging weight is also taken into account in determining the number of tests required.

Certain long forgings that have been quenched and tempered are required to be tested at both ends, and in these circumstances separate test bars are not permitted. This is because the intent is to check on furnace temperature uniformity as well as quenching efficiency. Temperature control for all furnaces is required by Specification A 788.

An important mechanical test requirement that could be overlooked applies to hubbed tube sheets and covers for Section VIII, Divisions 1 (Fig. UW13.3) and 2 (Fig. AD701.1) of the ASME Boiler and Pressure Vessel Code. These requirements are for the tension test to be located near the hub and oriented parallel to the longitudinal axis of the forging that is through the thickness, rather than in the tangential direction. This test, referenced in Supplementary Requirement S8 or in Specification A 788 by S12, would be in place of the requirements of Section 8 of the specification, but the number of tests required would still be dictated by the forging weight. The test location for quenched and tempered forgings does not specify extra discard as in the T × ¼T method, and for that reason does not include the t × 2t protocol for forgings that are contour machined before heat treatment. It should be remembered, however, that certain construction codes, such as Section VIII, Division 2 of the ASME Boiler and Pressure Vessel Code, do have test location requirements for quenched and tempered forgings that take precedence over the product specification.

Certified material test reports are required by the specification, as well as marking requirements that reflect the method of heat treatment.

A 336/A 336M-04, Alloy Steel Forgings for Pressure and High Temperature Parts

This is a companion forging to Specification A 266/A 266M and was originally written to cover alloy and stainless steel forgings for pressure vessels. Because of complexity, as seen today in Specification A 182/A 182M, the stainless steel forgings were broken out and included in a new Specification A 965/A 965M, Steel Forgings, Austenitic, for Pressure and High Temperature Parts.

As far back as the 1955 revision the manufacturing section included minimum forging reduction requirements for hollow forged cylinders and for small drums, forged solid and subsequently bored. This entailed reducing the cylinder wall thickness by at least half by forging on a mandrel, or, in the case of solid forged cylinders, reducing the ingot cross-sectional area by a factor of at least three. The difficulty with the latter requirement was that no credit for upset forging could be taken, and the use of large diameter ingots frequently meant that steel utilization could be very uneconomic. These details were dropped several years ago, but they can still be found in the specification as Supplementary Requirement S8, Forging Requirements.

The alloy materials parallel most of those in Specification A 182/A 182M, and the specification is intended for larger forgings. This is reflected in the testing requirements. It should not be inferred from this that the maximum forging weight of 10 000 lb (4.5 t) in Specification A, 182/A 182M, is considered to be small. The more onerous requirements in Specification A 336/A 336M as compared to Specification A 182/A 182M tend to promote the use of the latter specification for reasons of first cost rather than suitability for purpose.

A curious long standing feature of Specification A 336/A 336M is the provision in the scope clause for using the chemical composition, heat treatment, and mechanical test requirements of the seamless pipe specification A 335/A 335M for forgings otherwise complying with the forging specification. The background for this is not recorded, and it was not present in the 1955 revision. It is possible that thick walled, alloy steel, seamless pipe was used to manufacture items such as superheater headers for water-tube boilers by forging down the ends of seamless pipe, and it was requested that the headers so produced be certifiable to A 336. The compositions of several of the grades in Specifications A 335/A 335M and A 336/A 336M are essentially the same, but the tensile strength requirements differ for some grades. Although it is not currently a requirement, the source of the starting material should be identified as being from Specification A 335/A 335M in order to forestall possible complaints about the material not complying fully with the specification.

The alloy steels included in Specification A 336/A 336M are all of the molybdenum or chromium-molybdenum type with up to a nominal 9 % chromium content, as well as a 410 series martensitic stainless steel.

Heat treatment is covered in Section 6. The basic requirement is for the forgings to be annealed or normalized and tempered with tempering temperatures required to be between 1100°F (595°C) and 1350°F (730°C), depending on the composition. The specific temperatures are listed in Section 6. Austenitizing temperatures are specified for the more complex grades and stem from data supplied when the grades were introduced. These austenitizing temperature requirements concern Grades 22V, a modified 2¼Cr1Mo alloy, and Grades F91 and F911 that are modified 9Cr1Mo alloys, and are related to their elevated temperature properties. Liquid quenching and tempering of the forgings to Specification A 336/A 336M is permitted by agreement with the purchaser. This is permitted to improve notch toughness properties in order to meet construction code requirements, but three alloys, Grades F 22V, F3V, and F3Cb are required to meet specified Charpy V-notch impact test requirements. These materials are commonly used in catalytic petrochemical cracker columns. The yield to tensile strength ratios for the listed alloys are consistent with the normalize/temper heat treatment cycle, and it should be noted that these alloys have considerable hardenability, so that for the quenched and tempered state the yield strengths can be expected to be considerably higher than the specified minima. The materials are all required to meet a tensile strength range. This allows the tensile strength to be up to 25 ksi (175 MPa) above the specified minimum value. This falls into line with requirements from the ASME Boiler and Pressure Vessel Code. For those unfamiliar with the mechanical properties of steel, strength ranges are a method of ensuring that the ductility values are maintained at optimum levels; however, the range must be applied to *either* the tensile strength or yield strength, but *never* to both because the resulting operating window can be very narrow to nonexistent. Some notable military specifications carried this impossible handicap for a number of years.

The mechanical properties section includes the test specimen location requirements, and these depend on the type of heat treatment. For quenched and tempered forgings, the test location is more deep seated in the test prolongation (T × ¼T) or is related to a specific heat treated contour (t × 2t) than is the case for annealing or normalizing. These test location conventions are illustrated in Fig. 15.1. The dimension T is the maximum section thickness of the forging at the time of heat treatment. This could be the maximum wall thickness of a bored forging or the maximum thickness of a disk forging. Since heat is also extracted from the end faces of a cylinder or the periphery of a disk, the T discard is intended to show that the properties obtained are representative of the body of the forging remote from the ends. The number of tests is similar to the formula used in Specification A 266/A 266M and depends on the forging heat-treated weight, and in the case of quenched and tempered forgings on the heat-treated length.

Although it is anticipated that nondestructive testing would be included in the purchase order for forgings to this specification, perhaps to satisfy a construction code, this is not a mandatory specification feature, except for the case when forgings have been quenched and tempered. In this case a magnetic particle examination in accordance with Method A 275/A 275M to check for quench cracking is necessary.

Test reports are again mandatory and the marking must include a notation for the type of heat treatment used.

A 372/A 372M-03, Carbon and Alloy Steel Forgings for Thin Walled Pressure Vessels

First published in 1953, this specification occupies a niche for high-pressure gas storage cylinders that see wide use in commerce for static, portable, and mobile applications. They probably constitute the most common form of pressure vessel, but should not be confused with the tanks, usually called air receivers, that are connected to air compressors. This forging specification was the first that included high tensile strengths to be adopted by the ASME Boiler and Pressure Vessel code. Welded construction is not permitted, but seal welding, under the rules of the construction or application code is permissible after heat treatment. Welded repairs, again after quality heat treatment, are permitted only by agreement with the purchaser and again must comply with the construction or application code rules.

Three carbon steels and several alloy steels, ranging from a simple carbon-molybdenum grade to high strength nickel chromium molybdenum alloy steels, are included. A unique feature is that because of the geometry of the forgings the mechanical properties required reflect cooling from one side only, since the cylinder is essentially closed when heat-treated. Minimum tempering temperatures are specified ranging from 1000°F (540°C) to 1100°F (595°C), depending on the specified grade.

The use of seamless pipe as starting material is permitted in the scope. To make the vessel, the pipe ends are heated and forged shut or swaged. Because seamless pipe is the common starting material, flattening tests are required to demonstrate the ductility of the material. However, depending on the outside diameter of the vessel (D) and the wall thickness T, a bend test may be substituted for the flattening test. An outside diameter of 14 in. (355 mm) or less is one of the flattening test criteria, together with a D/T ratio of 10.0 or less. One of the problems with flattening tests on larger diameter and thick walled rings is the power required to collapse the ring and the safety measures necessary to guard against the ring slipping during the test.

Apart from the difficulties associated with immersion quenching an essentially closed cylinder—they have a tendency to want to float in the quench media—the condition of the test material must also be considered since, to be representative, this too must be cooled only from the OD surface. The ends of the test ring must, therefore, be closed off during heat treatment. Spray quenching in a rig that supports and rotates the piece would be a suitable process for this type of product.

Magnetic particle examination to Test Method A 275/A 275M is required for all quenched and tempered forgings.

As is the case for forgings to Specification A 336/A 336M, a tensile strength range of 25 ksi (175 MPa) is required to be met for both the carbon and alloy steel grades.

A 508/A 508M-04b, Quenched and Tempered Vacuum Treated Carbon and Alloy Steel Forgings for Pressure Vessels

Originally published in 1964, this specification was written to provide for the supply of premium steel pressure vessel forgings for the nuclear reactor building program. Made to the ASME Section IIA Specification SA-508/SA-508M, forgings are used in the construction of nuclear power plants in many parts of the world. Reference is made to Section III of the ASME Boiler and Pressure Vessel Code by means of a supplementary requirement for fracture toughness testing rules for specific classifications of nuclear vessel components. The specification remains the most demanding available in North America for weldable forgings for pressure vessel applications, with mandatory nondestructive examination requirements and mechanical property assurance.

The current availability of vacuum degassed ladle refined steel making processes as a starting point for large steel forgings has the potential to enhance further the already high quality expected from this specification.

While the two carbon steels are identical in composition to those found in specifications, such as A 105/A 105M, A 266/A 266M, and A 350/A 350M, the remaining alloy steel grades are more specialized.

Grade 2 was originally developed for reactor vessel components and is a nickel-chromium-molybdenum alloy. The alternative Grade 3 alloy is a manganese-nickel-molybdenum material. In the Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) systems, the vessel ID surfaces are weld overlaid with austenitic stainless steel, and with some of the high deposition rate systems there was a tendency for under clad cracking in the Grade 2 base material. The introduction of the Grade 3 material was seen as a solution to this problem, and this soon became the dominant reactor pressure vessel material. In Europe, Japan, and Korea, Grade 3 has been used extensively for high integrity reactor and steam generator components [3–5].

Grade 4N is a high strength weldable nickel-chromium-molybdenum steel often referred to as HY-80 (Grade 4N, Class 1) and HY-100 (Grade 4N, Class 2). The suffix N appeared between the 1984a and 1995 revisions but the origin is obscure, possibly meaning "nuclear" as opposed to "marine," the original application of these steels. These high toughness steels were used frequently for vessel supports designed to withstand seismic loads, but together with Grade 5, have been used also for quartz crystal growing vessels.

Grade 5 is also available as Class 1 (85 ksi (590 MPa) yield strength) or Class 2 (100 ksi (690 MPa) yield strength), which has the same chemistry as Grade 4N except that there is a vanadium range of 0.02 to 0.08 % in contrast to the vanadium requirement of 0.03 % maximum for Grade 4N. Vanadium besides effecting grain refinement is a carbide former and its presence in steel tends to increase the tempering temperature required for obtaining a given hardness. Vanadium also delays the onset of grain coarsening in the austenitic temperature range. Its presence is not always considered to be advantageous in weldments because during postweld heat treatment there is a tendency to resist softening in the weld heat affected zone.

Grades 22, 3V, and 3VCb are the modified chromium-molybdenum steels that are popular in the petrochemical industry, and represent the expanded use of the specification outside of the nuclear reactor field.

An unusual and very important provision in Specification A 508/A 508M is that the manufacturer must make and report a product analysis for the forging, and that tolerances are not permitted for all of the included elements. Carbon is restricted strictly to the heat analysis limits, and the same limitation applies to sulfur, phosphorous, and the additional elements required for Grades F3V and F3VCb.

Heat treatment is covered in Section 4 under the general heading of Materials and Manufacture. As the specification title indicates, all of the material grades are required to be quenched and tempered, and forgings must be permitted to transform after hot working before being reaustenitized for heat treatment. Minimum subcritical tempering temperatures are specified for all of the grades, but some of these can be modified by the use of supplementary requirements. The tempering temperatures range from 1100°F (595°C) to 1250°F (675°C) depending on the grade. Extensive experience with Grade 2 Class 1 forgings shows that the minimum yield strength is easy to attain even in deep-seated tests in large forgings with carbon contents as low as 0.18 %, and that the limiting factor is the tensile strength. This is demonstrated by the following actual test data. In order to meet the necessary notch toughness criteria, a fine grain size is vital, either by the use of grain refiners or suitable heat treatment.

Chemical Composition of Actual Grade 2 Forgings

Element	Specification %	Forging A %	Forging B %
Carbon	0.27 max.	0.19	0.20
Manganese	0.50–1.00	0.73	0.75
Phosphorous	0.025 max.	0.009	0.007
Sulfur	0.025 max.	0.010	0.010
Silicon	0.15–0.40	0.25	0.31
Nickel	0.50–1.00	0.76	0.86
Chromium	0.25–0.45	0.41	0.42
Molybdenum	0.55–0.70	0.63	0.66
Vanadium	0.05 max.	0.02	0.00
Aluminum	*	0.006	0.005

* Aluminum additions not permitted by purchase order

Forging Dimensions:

Forging A:	23-in. (575-mm) diameter (solid) (T), 10-ft (3-m) long
Test Location:	23-in. (575-mm) end discard (T) and 5.75 in. (144 mm) under the OD surface (¼T).
Forging B, Cylinder:	19.5-in. (490-mm) ID × 28.5-in. (715-mm) OD. Wall thickness 4.5 in. (112.5 mm) (T). Length 24 ft (7.4 m)
Test Location:	End discard 4.5 in. (112.5 mm) (T), and 1.125 in. (28 mm) under the OD surface [¼T].

Heat Treatment:

Item	Forging A Section 23 in. (575 mm)	Forging B Section 4.5 in. (112.5 mm)
Heat treatment	°F (°C)	°F °C
Normalize	1680 (915)	1680 (915)
1st Austenitize	1580 (860)	1580 (860)
2nd Austenitize	1450 (790)	1450 (790)
Temper	1180* (640*)	1280 (690)
*from S13		
Tensile	UTS YLD E% RA% ksi [MPa]	UTS YLD E% RA% ksi [MPa]
Required	80 50 18 38 (550) (345)	80 50 18 38 (550) (345)
T × ¼T	84.3 60.9 28 66 (581) (420)	83.9 58.6 30 73 (578) (404)
Charpy V @ 10°F (−12°C)	30 ft-lbf avg. (41 J avg.) 25 ft-lbf (34 J) min. single	30 ft-lbf avg. (41 J avg.) 25 ft-lbf (34 J) min. single
T × ¼T	41.5, 64, 41 ft-lbf (56, 87, 56 J)	185, 131, 110 ft-lbf (251, 178, 149 J)

*Lower tempering temperature permitted by Supplementary Requirement S13

Note that a similar intercritical heat treatment procedure has been used successfully on reactor vessel nozzle forgings to the Grade 3 requirements.

Nil Ductility Test Temperature (Per ASTM Specification E 208):

Forging A: 10°F (−12°C)
Forging B: −20°F (−29°C)

Notice that the heat treatments applied to these forgings utilized a normalize and double water quench and temper cycle. In the first example, Forging A was a 23-in. diameter solid core bar that had been trepanned from a 44-in. (1100-mm) diameter forging, and was used to demonstrate that with a suitable steel chemistry the intercritical heat treatment cycle is capable of developing fairly uniform tensile properties and acceptable notch toughness in very thick sections. Similar values were obtained at the center of this bar. In the case of Forging B, this was made from a heat that did not include any grain refining elements. The use of aluminum was not permitted, and the aim amount of vanadium (0.03 %) was not added. The required Charpy V-notch impact values could not be obtained after a conventional normalize, water quench, and temper cycle. The reheat treatment using the intercritical cycle gave the excellent Charpy V-notch test results shown in the table at the required test temperature.

The specification mechanical properties are listed in Section 6. Requirements for test specimen location and for the number of tests are quite rigorous and require careful study. Guidance on heat-treated section size limitations for the various grades are given in 6.1.6.2 as these relate to the T × ¼T test location. The limitations here are dictated by the ability to meet the impact test requirements, but for Grades 1, 2, and 3 this can be enhanced considerably by the use of the intercritical heat treatment cycle as the quoted examples show. This type of heat treatment is not effective for Grades 4N, 22, 3V, and 3VCb since these require a martensitic transformation.

Although the specification calls for the test specimen orientation to be taken parallel to the direction of maximum hot working, it should be noted that construction codes sometimes specify an orientation at right angles to this, and this aspect should be checked carefully to ensure compliance, remembering that clean steels assist materially in transverse testing.

Nondestructive examination, Section 8, includes acceptance criteria for both magnetic particle and ultrasonic examinations. The purchaser should be aware that any surface machining of forgings after delivery will negate the previous magnetic particle test results in the remachined areas. It should be observed also that the magnetic particle examination is required to be by the continuous procedure in accordance with Method A 275/A 275M. Because of the complexity of certain large forgings, such as vessel nozzles, it is possible that some of the ultrasonic examination will have been performed prior to the quality heat treatment. This should be apparent from a written ultrasonic examination procedure, and this is something that the knowledgeable purchaser should require.

Repair welding of forgings is allowed only with the purchaser's permission, and must conform to the requirements of Section IX of the ASME Boiler and Pressure Vessel Code.

A variety of supplementary requirements is included in the specification. Many of these relate to chemistry restrictions, and S9 applies particularly for copper and phosphorus in forgings that will be in high irradiation zones of the reactor pressure vessel.

Numerous papers [3–7] have been published on the application of forgings to this specification, particularly for Grade 3. The trend appears to be towards very low sulfur and phosphorous levels [8] for this material, including a suggested sulfur plus phosphorous maximum of 0.005 %.

A 541/A 541M-95, Quenched and Tempered Alloy Steel Forgings for Pressure Vessel Components

This is a companion specification to A 508/A 508M and was intended to be used for smaller forgings for pressure vessels. Vacuum degassing of steel was not as commonplace when the specification was first published in 1965 as it is today, and this is not a requirement of the specification. The steel grades generally parallel those of Specification A 508/A 508M in terms of chemistry and strength levels, but there are some differences.

Grade 1C is a high strength carbon steel with carbon limited to a maximum of 0.18 %. The steel has a vanadium requirement of 0.02–0.12 %, but the manganese is limited to a maximum of 1.30 %. The tensile strength is 80–105 ksi (550–720 MPa) and a yield of 50 ksi (340 MPa) minimum. The suggested maximum heat-treated section size is 4 in. (100 mm) for the T × ¼T test location. The origin for this material in the specification is not remembered, although it may be connected with API [9]. The restricted carbon content is a significant limiting factor, especially when it is remembered that the mandatory product analysis, following the lead of Specification A 508/A 508M, does not allow a tolerance for carbon and vanadium. The implication of this is that it would be risky to attempt to make a heat of steel to Grade 1C with an aim carbon very close to 0.18 %.

Grade 11, Class 4, has the same tensile requirements as Grade 1C, but this is a 1½Cr-½Mo alloy steel that is very similar to Grade F11 of Specification A 336/A 336M. The reason for the Class 4 designation is not clear since the material only appears once in the specification, but this may be related to Specifications A 182/A 182M and A 336/A 336M where Grade F11 appears with three strength classes.

The 2¼Cr1Mo alloy Grade 22 appears with three strength classes, one of which, Class 3, has the carbon range restricted to the higher end, but curiously with lower tensile strength requirements.

Nondestructive testing is not mandatory as it is in Specification A 508/A 508M, but provision for such examinations is made in the list of supplementary requirements.

A 592/A 592M-04, High Strength Quenched and Tempered Low-Alloy Steel Forged Fittings and Parts for Pressure Vessels

First published in 1968, this specification was written to cover weldable forged pressure vessel components to match the plate specification, A 517/A 517M, Pressure Vessel Plates, Alloy Steel, High Strength, Quenched and Tempered. The term "fitting" should not be confused with piping fittings covered by Subcommittee A01.22, but would refer to items such as nozzles or shell rings.

The scope section lists thickness limits for the three composition grades. These grades are essentially identical in composition (and in name) with three of the six grades included in A 517/A 517M, and the plate specification also includes thickness limitations; however, these do not correspond exactly with those in the forging specification (see Table 17.1).

It will be seen that there are significant differences in thickness limits for Grades E and F. The plate thickness values will be the as rolled and heat treated thicknesses, but the only significant thickness for forgings, since these are almost invariably subject to machining, is the as heat-treated thickness.

Of the three steels, Grade E is by far the most potent in terms of hardenability being nominally a 1.75 % chromium-0.5 % molybdenum steel with boron additions that are protected by titanium.

The tensile strength requirements must be reviewed carefully, since these are dependent on the heat-treated section size of the forgings, and fall into two levels with the break at 2.5 in. (65 mm). This follows the same pattern as the plates to Specification A 517/A 517M. The minimum tensile strength of 115 ksi (795 MPa) applies for (heat treated) thicknesses up and including 2.5 in. (65 mm), and this drops to 105 ksi (725 MPa) for greater thicknesses. These limits are recognized in Section IID of the ASME Boiler and Pressure Vessel Code, and should be borne in mind for vessel designs to other criteria. It should be noted, that Charpy impact testing is a specification requirement, particularly since this does not appear in a table. Instead of an average absorbed energy requirement, a minimum lateral expansion measurement of 15 mils (0.015 in.) (0.38 mm) is called for. This complies with the ASME Boiler and Pressure Vessel Code rules for steels with tensile strengths of 95 ksi (655 MPa) or higher. It should be noted that special rules apply for retesting in the event of failure of one specimen to meet the required minimum lateral expansion value.

A 649/A 649M-04, Forged Steel Rolls Used for Corrugating Paper Machinery

This specification was first published in 1971. The original requirement was included in Code Case 1398 issued by the ASME Boiler and Pressure Vessel Code. The rolls covered by this specification are used in machines that manufacture the familiar corrugated paperboard that is used by the container industry. Originally the corrugating roll stack used a pair of matched rolls with contoured longitudinal grooves or flutes, and an upper plain surfaced pressure roll. Some later machine designs have eliminated the pressure roll. The rolls are hollow and are steam heated. For this reason, particularly for the longer and larger diameter rolls, they are required to be classified as pressure vessels according to Section VIII, Division 1 of the ASME Boiler and Pressure Vessel Code. However, the design is complicated by the fact that the rolls are subject to high external mechanical loads in service, quite apart from the forces exerted by the internal steam pressure. Paper traveling at fairly high speeds and passing between the heated rolls is corrugated and then glued to a plain facing paper sheet. This type of machine is known as a "single facer." A second plain sheet is glued to the opposite side of the corrugated assembly to finish the board. Multiple layer corrugated boards are also made for special applications. The grade of paper used has become increasingly abrasive, particularly when the pulp is made from trees harvested by plucking the trunk from the ground by the roots, so that wear of the corrugated roll surfaces is a problem, since this will increase paper usage and impact the dimensions of the corrugated board. This necessitates regrinding of the rolls, and this is effectively limited up to a maximum

TABLE 17.1—Comparison of the Maximum Thickness Limitations in ASTM A 517/A 517M and A 592/A 592M

Specification	Grade A	Grade B	Grade E	Grade F	Grade J	Grade P
A 517/A 517M	1.25 in. (32 mm)	1.25 in. (32 mm)	6 in. (150 mm)	2.50 in. (65 mm)	1.25 in. (32 mm)	4 in. (100 mm)
A 592/A 592M	1.50 in. (38 mm)	—	4 in.* (100 mm)*	4 in.* (100 mm)*	—	—

*Heat treated thickness

of about six regrinds. For these reasons, the rolls are not made from conventional pressure vessel materials, but rather from wear resisting materials that have the strength to withstand the high external loads imposed on the corrugating stack, as well as the internal working pressure. High surface hardness is needed to withstand these service conditions, so that the steels used for the roll shells have a higher carbon content than those normally used for pressure vessels.

In order to isolate such materials from general use in the ASME Boiler and Pressure Vessel Code, this specification was written to include not only materials but also construction and design rules so that it is unique among the product specifications in both ASTM and ASME. The specification is essentially a complete component manufacturing scheme, including as it does some design criteria, steel manufacture, forging, machining, heat treatment, mechanical testing, assembly, final hydrostatic testing, and nondestructive examination.

The scope clause includes essential information for the use of the standard from the aspects of both design and roll manufacture. The rolls consist of two major parts, the shell and the trunnions or journals. Commonly, a pair of trunnions is fitted into the ends of a heat-treated roll shell; however, provision is made for designs incorporating an integral journal at one end. Typically, the trunnions or journals are shrink-fitted into the counterbored ends of the roll shell, and seal welded. For some European applications, seal welding is not permitted and shrink fitting alone is used. In this case, great attention must be paid to the surface finish of the mating parts to avoid steam leakage. Bolting the trunnions to the roll shell is also permitted, but again the common construction is to shrink fit and seal weld.

The pressure rolls, when used, are typically made from Class 3, a carbon steel similar to SAE 1050. These are thick walled rolls, usually normalized and tempered, and invariably induction hardened.

The corrugating rolls are higher strength alloy steels, the common materials being Class 1A (modified SAE 4150) and Class 1B (modified SAE 4350). An alternate but rarely used material for corrugating rolls is Class 5, a substantially modified SAE 1050 steel. The trunnions are made from a choice of a carbon steel (Class 4) similar to that of ASTM A 266 Grade 1, or Class 3 that is essentially SAE 4130. The choice of SAE 4130 for the trunnions is at first sight startling, in view of the low strength requirement of a minimum 60 ksi (415 MPa) tensile strength and a minimum yield strength of 30 ksi (205 MPa). The explanation is an example of the economics of availability and low cost. Going back in history to the time when demand for rolls for corrugating machines first arose, and before there was any need to classify them as pressure vessels, a prominent roll manufacturer also produced forged steel molds for the production of ductile cast iron water pipe by centrifugal casting. The mold material was similar to SAE 4130, and many of the forged molds were trepanned before being heat treated, leaving a core bar. Trunnions for corrugating rolls were economically produced by reforging lengths of pipe mold core bar, so that when the need arose to write a specification for the manufacture of corrugating rolls, the 4130 chemistry was included. Currently most trunnions are produced from the carbon steel Class 4 material.

The scope goes on to detail the roll inside diameter limits, as well as wall thickness, the maximum operating temperature, and working pressure. Requirements also include limitations on the stresses imposed on the roll shells and trunnions from the combined effects of internal pressure and external loads. As machine designs have developed over time, so too have the material options and size limits changed. For example, the maximum inside diameter has been increased from 12 in. (300 mm) in 1981 to 30 in. (760 mm) currently. Similarly, the use of corrugating roll materials for the pressure roll application is now allowed.

Heat treatment requirements for the roll shells and trunnions are specified together with the admonition that the roll shells must be bored prior to heat treatment. Tension testing is required as well as surface hardness testing.

The pressure rolls are required to be surface hardened, originally by flame hardening, as shown in Fig. 12.1 and more commonly now by induction hardening. As the paper stock became more abrasive, a move to hardening the corrugating roll surfaces took effect, and now almost invariably the corrugating roll surfaces are induction hardened. A supplementary requirement has been provided to permit this, either before or after forming the flutes. Magnetic particle examination, very necessary when induction hardening and surface grinding are involved in manufacturing procedures, completes the manufacturing process together with the final hydrostatic pressure test. When the roll flutes are formed after induction hardening, a technique known as creep feed grinding is used. This enables the entire flute form to be produced in one or two passes. Such heavy grinding requires special grinding wheels that permit the coolant to be pumped through the wheel itself, as well as the usual external supply.

A 723/A 723M-03, Alloy Steel Forgings for High-Strength Pressure Component Application

First published in 1975, this specification was written to fill the need for alloy steel forgings used in the manufacture of very high pressure vessels, such as those required for quartz crystal culture, as well as both hot and cold isostatic presses that are used in the production of high integrity ceramic components, densification of precision castings, or production of hot isostatically-pressed components such as those covered by Specifications A 988 Hot Isostatically-Pressed Stainless Steel Flanges, Fittings, Valves and Parts for High Temperature Service, and A 989, Hot-Isostatically Pressed Alloy Steel Flanges, Fittings, Valves and Parts for High Temperature Service. Further applications for forgings in these materials are found in the petrochemical industry.

The alloy steels included in the specification are of the nickel, chromium, molybdenum, vanadium type that are frequently referred to as gun-steels because of their use in artillery gun barrels and breech blocks, and may be considered as derivatives of the SAE 4340 composition. A general admonition that the steels are not considered to be suitable for welded construction is included in the scope.

In contrast to the usual pressure vessel forging specifications, specific strength levels are not tied to particular compositions; rather, three composition grades are specified with increasing nickel ranges, and six strength ranges as follows:

Element	Grade 1 %	Grade 2 %	Grade 3 %
Carbon	0.35 max	0.40 max	0.40 max
Manganese	0.90 max	0.90 max	0.90 max
Phosphorus	0.015 max	0.015 max	0.015 max
Sulfur	0.015 max	0.015 max	0.015 max
Silicon	0.35 max	0.35 max	0.35 max
Nickel	1.5–2.25	2.3–3.3	3.3–4.5
Chromium	0.80–2.00	0.80–2.00	0.80–2.00
Molybdenum	0.20–0.40	0.30–0.50	0.40–0.80
Vanadium	0.20 max	0.20 max	0.20 max

Minimum Property	Class 1	Class 2	Class 2a	Class 3	Class 4	Class 5
UTS ksi (MPa)	115 (795)	135 (930)	145 (1000)	155 (1070)	175 (1205)	190 (1310)
Yield (0.2 %) ksi (MPa)	100 (690)	120 (825)	130 (895)	140 (965)	160 (1105)	180 (1240)
Elongation (4D)	16	14	12.5	13	12	10
Reduction Of Area	50	45	43	40	35	30
Avg. Charpy V Min. Single Value Ft-lbf; [J] 40°F (4.5°C)	35 (47) 30 (41)	30 (41) 25 (34)	28 (38) 23 (23)	25 (34) 20 (27)	20 (27) 15 (20)	12 (16) 10 (14)

The strength ranges reflect the required quench and temper heat treatment, with high yield strength to tensile strength ratios.

Generally, with the nickel-chromium-molybdenum steels, the Charpy impact test results improve with increasing yield to tensile strength ratios reflecting more complete transformation to martensite on quenching. A minimum tempering temperature of 1000°F (540°C) is required, thus avoiding low ductility or toughness problems that might be encountered when tempering at lower temperatures. When control of phosphorus and some other tramp elements such as arsenic and antimony was a problem, quenching forgings after completion of tempering was often done in order to cool quickly through the temper embrittlement range. This practice is still used today, but for a modern clean and low phosphorous steel, little if any improvement can be seen in the ductility and toughness properties of forgings that have been air cooled from the temper and those that have been water quenched after tempering. As mentioned in the section dealing with heat treatment, a difficulty that can occur in forgings that have been water cooled after tempering is one of severe distortion after subsequent machining if stock removal is not symmetrical.

The mechanical testing requirements for forgings in Specification A 723/A 723M are intended to ensure that the required properties have been achieved uniformly both around the circumference and from end to end. For large, heavy, and long forgings, tests would be required at both ends, this being dependent on heat-treated weight and length. Having good furnace control at a minimum is essential for the consistent heat treatment of steels of this type.

Water quenching of forgings is desirable in order to develop optimum properties, and for this reason the carbon content should be restricted to a limit of about 0.33 %, but in no case higher than 0.35 %. The SAE 4340 alloy is generally regarded as requiring an oil quench, although suitable polymer quenchants are commonly used. Water quenching this steel can frequently result in cracking. For the high nickel Grade 3 material, particularly when used for bored forgings, oil quenching is generally used.

The matching of steel composition grade to strength class is intended to be left to the forging manufacturer who will decide based on the required class and the forging size and shape at the time of heat treatment. The producer, however, does have the option to make this choice.

In keeping with the high integrity required for the operating conditions of high pressure vessels, nondestructive examination by magnetic particle and ultrasonic methods are required.

Research on reducing temper embrittlement tendencies in the nickel-chromium-molybdenum alloy steels has shown [10] that reducing phosphorus, tin, silicon, and manganese levels is helpful. This work produced a term known as the J Factor, {$J = (\mathrm{Mn} + \mathrm{Si})(\mathrm{P} + \mathrm{Sn}) \times 10^4$} that is useful for indicating the tendency for embrittlement in a given steel. This tendency reduces steadily from a J factor of 200 to 1 of 60; beyond this the gains are somewhat less [11]. It has been suggested also [11] that sulfur should be restricted to 0.006 % maximum, together with a reduced manganese range of 0.10–0.20 %. While this is a subject for future consideration, it should probably be coupled with the toughness criteria.

A 765/A 765M-01, Carbon Steel and Low Alloy Steel Pressure Vessel Component Forgings with Mandatory Toughness Requirements

Originally published in 1979, this specification parallels the flange and fittings Specification A 350/A 350M in terms of most of the materials, but the testing provisions are more appropriate to large forgings such as tube sheets, nozzles, and shell sections.

Charpy V-notch impact test temperatures are specified for each of the five steel grades with the proviso that the purchaser can specify a different temperature at the time of the inquiry or order. If a change in impact test temperature is not made by the purchaser then the temperature given in the specification must be used. It should be noted that in the event that a different test temperature is specified, then that temperature must be marked on the forgings according to the instructions listed in the marking paragraph. The impact test temperature must also be noted in the certification.

Heat treatment of the forgings is required, and the manufacturer has the option of normalizing and tempering or quenching and tempering. If the purchaser has specific requirements for heat treatment, these would have to be included in the order. The location and number of the mechanical test specimens is governed by the specification, and the use of separately forged test blocks is limited to forgings with heat-treated weights of no more than 1000 lb (455 kg). For small forgings up to 500 lb (230 kg) in heat treated weight, one mechanical test set is required for each heat in each heat treatment charge; however, for continuous furnaces with temperature recording controls one test per heat in an 8-h shift is permitted. For larger forgings each forging must be tested. This differs considerably from the requirements of Specification A 350/A 350M.

The specification is intended to give assurance that the forgings will possess the required tensile and Charpy V-notch toughness.

A 859/A 859M-04, Age-Hardening Alloy Steel Forgings for Pressure Vessel Components

This specification was first published in 1986 and currently includes two alloy steels. The original material, now called Grade A, is a nickel-chromium-molybdenum steel with copper that produces an age hardening effect from fine precipitates after solution treatment and tempering. It is available in two strength classes. The carbon content is low at 0.07 % maximum, and the material lends itself to welded construction while conferring good low temperature toughness. This alloy appears in other forging specifications as Grade LF787 in Specification A 350/A 350M, and as Grade L5 in Specification A 707/A 707M. As rolled plate, the alloy is included in A 736/A 736M Pressure Vessel Plates, Low Carbon Age-Hardening Nickel-Copper-Chromium-Molybdenum-Columbium and Nickel-Copper-Manganese-Molybdenum-Columbium Alloy Steel. Other chemistry and higher strength variations of this material have appeared, and these have found extensive use in offshore oil rigs, particularly in the Gulf of Mexico.

This alloy, particularly in its higher strength forms, is prone to hydrogen flake damage, even when using vacuum degassed steels, so that precautions, such as a thermal flake prevention cycle done typically in the range 1200–1250°F (650–675°C), should be taken after forging.

Welding procedures often do not include post-weld heat treatment because of a tendency for heat affected zone cracking during such cycles. Furthermore, heat affected zone hardness values do not tend to peak because of the low carbon content of the base material.

The forgings are required to be heat-treated, the Class 1 strength level being normalized and aged and the Class 2 higher strength forgings being liquid quenched and aged. The age hardening part of the cycle is required to be done in the range of 1000–1225°F (540–665°C).

A second steel called Grade B is also known as HSLA-100. This alloy also includes copper and has a narrow carbon range of 0.02–0.040 %. The nickel and molybdenum contents are appreciably higher than those in Grade A. The tension test requirements for Grade B are unusual in that they include a range for yield strength and a minimum tensile strength. The producer has to take careful note of this.

Although forgings made to this specification are intended for pressure retaining components, application for structural applications is not uncommon. Because of the precipitation hardening characteristics the section size capability is quite large.

A 965/A 965M-02, Steel Forgings, Austenitic, for Pressure and High Temperature Parts

This specification, first published in 1996, was the upshot of a decision to separate the ferritic and austenitic material requirements for forgings made to Specification A 336/A 336M. The current complexity of Specification A 182/A 182M is sufficient to show why the change was proposed for Specification A 336/A 336M.

At the time that A 965/A 965M was written no duplex stainless steels were included in the scope. These will be included in a separate forging specification.

Twenty-two austenitic steel compositions that used to be included in Specification A 336/A 336M form the content of A 965/A 965M. These include the standard 300 series steels together with the low carbon L series grades, the nitrogen containing LN grades, and the H grades, the latter being intended for high temperature service. The H grade austenitic stainless steels carry a mandatory grain size requirement of ASTM 6 or coarser. This requirement was carried over from The ASME Boiler and Pressure Vessel Code in order to permit the use of increased allowable stress values at higher temperatures.

Solution annealing of the forgings is required, and this must be done as a separate operation from the forging cycle. The so-called in process annealing, whereby on completion of forging, provided the temperature meets the specification solution treatment temperature conditions, the forging is simply quenched to meet the solution anneal requirement, is not permitted.

The tension test requirements for Specification A 965/A 965M are more stringent than is the case for the forged flange and fitting Specification A 182/A 182M, in that each forging weighing over 5000 lb (2250 kg) is required to be tested.

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18

Steel Forgings for Turbines and Generators

THIS GROUP OF FORGINGS CONSTITUTES MAINLY the rotor and disk or wheel components used in steam and gas turbines and electrical generators. The integrity of these components is critical [1] because they are generally large, rotate at high speeds, and in the case of steam turbines are confined under high pressure in steam chests. It will be recalled that concern for the safety of turbine and generator rotors spurred the introduction of vacuum degassing in steel making and the development of ultrasonic test methods for the volumetric examination of heavy sections. Ten ASTM forging specifications fall into this category. It should be noted that although these are intended to be stand alone specifications, essential input must be included in the purchase order, not the least of which is a drawing showing the required mechanical test locations.

The development of forging materials for turbine and generator rotors is an ongoing process as illustrated by the number of technical papers on the subject contributed to the meetings of the International Forgemasters. Held at intervals of approximately three or four years, these meetings attract a great deal of interest from producers and users alike.

A 288-91, Carbon and Alloy Steel Forgings for Magnetic Retaining Rings for Turbine Generators

This specification covers forged magnetic retaining rings, and eight strength classes are included as well as three steel compositions, also referred to as classes. The specification was originally published in 1946, but dates back to an Emergency Specification ES-21 from 1943. In the 1955 revision the specification referred only to seven classes of tension test requirements with no chemical requirements beyond limits on the product analysis tolerances for sulfur and phosphorus. The absence of heat chemical requirements probably reflected the practice of supplying forgings to proprietary compositions, and is an interesting reflection on the development of consensus standards. One additional (higher) strength class was added over the years, together with three chemical compositions, and the term Class was retained for the latter.

It should be noted that vacuum degassed steel is required for Classes 4 through 8 (the nickel-chromium-molybdenum alloy steels) and also for the thicker walled Class 3 rings where nickel is also required. This is because of the risk of hydrogen flake damage in these triple alloy steels. The purchaser would be well advised to make vacuum degassing mandatory for any forged rings purchased to this specification. Charpy impact testing at room temperature is mandatory, and contrary to the common use of a separate test bar for ring forgings, the tension and impact tests must be taken from a prolongation of the retaining ring. Machining before heat treatment is also required.

A 289/A 289M-97, Alloy Steel Forgings for Nonmagnetic Retaining Rings for Generators

This is a very specialized product used to restrain the windings of generator rotors [2–4]. Since the requirements tend to be conflicting—high strength and essentially nonmagnetic—the starting material is austenitic, and only the electroslag remelting process is now applicable. This is probably the only ASTM material specification restricted to this method of steel making. One steel composition can be purchased to eight strength grades ranging in minimum tensile strength from 145 to 200 ksi (1000–1380 MPa) and in yield strength from 135 to 195 ksi (930–1345 MPa), giving yield strength to tensile strength ratios in the range of 93–97.5 %. There is an admonition that the yield strength at an offset of 0.2 % may not exceed the tensile strength. Charpy impact testing at room temperature is required, and the specimen location in the test prolongation is specified.

Originally included in Emergency Specification E 21 in 1943, the nonmagnetic retaining ring Specification A 289 appeared in 1946 and included two medium to high carbon manganese-nickel and manganese-nickel-chromium alloy steels. These were not required to be heat treated, and there was no provision for cold working the rings. The highest tensile strength was 140 000 psi (965 MPa) with a yield strength of 105 000 psi (725 MPa) giving a yield to tensile strength ratio of 75 %, a far cry from today's material. Over time various manganese austenitic steels have been included in the specification, and the requirement for extensive cold working was introduced to increase the strength. The current steel is nominally a low carbon 19 % manganese-19 % chromium steel with a significant nitrogen content of about 0.6 % that could be produced in a pressurized ESR furnace [5].

The cold working, while giving high tensile and yield strengths must not induce significant magnetism through the breakdown of austenite, and a magnetic permeability limit is imposed.

Aside from the restricted melting requirements, the cold expansion process for the rings requires specialized equipment, so that the number of producers worldwide is very limited.

An option for elevated temperature tension testing at 200–220°F (95–120°C) is included by means of a supplementary requirement.

A 469/A 469M-04, Vacuum-Treated Steel Forgings for Generator Rotors

This specification was first published in 1962, and appears to have replaced Specification A 292 that in turn stemmed from another Emergency Specification E 23 that was used from 1943 to 1946. The new specification reflected the introduction of vacuum degassing into the steel making process and the improvement in resistance to hydrogen flaking. The vacuum degassing operation also permitted significant easing of the long post forge heat treatment cycles that were used to assist in the diffusion of hydrogen.

The following tables enable the steel compositions from the A 292-55 specification to be compared to those of the current A 469-04a revision. It will be seen that carbon and manganese are more restricted, minimum nickel requirements have been increased, chromium restrictions relaxed, and the molybdenum and vanadium requirements more defined. Sulfur and phosphorous limits have been drastically reduced.

The introduction of the nickel-chromium-molybdenum-vanadium steels for the higher strength rotors is another significant change from the original Specification A 292.

This comparison of the original generator rotor Specification A 292 and the current A 492 is of interest not only in tracing material and heat treatment development, but also in comparing different materials for the same strength levels and application and changing design criteria. The heat treatment requirements are markedly different in Specification A 469 where, unless otherwise specified, forgings must be quenched and tempered, compared to Specification A 292 that only permitted annealing or normalizing and tempering. Besides the change in heat treatment, the significantly reduced levels of sulfur and phosphorus are major contributors to the ductility improvement. Another important feature is the comparison of the ductility and toughness requirements for Grades 4 through 7. The differences here lie in the use of the nickel-chromium-molybdenum-vanadium alloy steel for Grades 6 and 7 and the nickel-molybdenum-vanadium steels for Grades 4 and 5.

The requirement for a maximum fracture appearance transition temperature (FATT) is an added fracture toughness feature, aimed at reducing the risk of brittle fracture, and is almost unique to the turbine and generator rotor forging specifications. Like the ductility values mentioned above,

A 292-55 Chemical Requirements

Element %	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9
C (max)	0.35	0.45	0.30	0.30	0.32	0.32	0.35	0.35	0.40
Mn (max)	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
P (max)	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
S (max)	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
Si	0.15/0.35	0.15/0.35	0.15/0.35	0.15/0.35	0.15/0.35	0.15/0.35	0.15/0.35	0.15/0.35	0.15/0.35
Ni (min)	. . .	. . .	1.75	1.75	2.25	2.25	2.25	2.50	2.50
Cr (max)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.75
Mo (min)	. . .	. . .	0.30	0.30	0.35	0.40	0.40	0.40	0.75
V (min)	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03

A 469-04a Chemical Requirements

Element %	Grade 2	Grade 3	Grade 4	Grade 5	Grade 6	Grade 7	Grade 8
C (max)	0.25	0.27	0.27	0.31	0.28	0.28	0.28
Mn (max)	0.60	0.60	0.70	0.70	0.60	0.60	0.60
P (max)	0.015	0.015	0.015	0.015	0.015	0.015	0.015
S (max)	0.015	0.015	0.015	0.015	0.015	0.015	0.015
Si (max)	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Ni (min)	2.50	2.50	3.00	3.00	3.25/4.00	3.25/4.00	3.25/4.00
Cr (max)	0.50	0.50	0.50	0.50	1.25/2.00	1.25/2.00	1.25/2.00
Mo	0.20/0.50	0.20/0.50	0.20/0.60	0.20/0.70	0.30/0.60	0.30/0.60	0.30/0.60
V	0.03 Min	0.30 min	0.30 min	0.05/0.15	0.05/0.15	0.05/0.15	0.05/0.15

A 292-55 Mechanical Properties

Property Ksi (MPa)	Gr. 2	Gr. 3	Gr. 4	Gr. 5	Gr. 6	Gr. 7	Gr. 8
UTS Radial Test	80 (550)	90 (620)	100 (690)	110 (760)	100 (690)	110 (760)	120 (825)
Yield 0.02% Ksi (MPa)	55 (380)	70 (485)	80 (550)	90 (620)	80 (550)	90 (620)	100 (690)
E%	20	20	17	15	18	17	16
RA%	50	50	45	40	55	50	45
FATT max F (C)	100 (38)	100 (38)	120 (49)	175 (80)	0 (−18)	20 (−7)	40 (4)
Charpy V Radial Tests Room Temp. ft-lbf (J)	30 (40)	30 (40)	25 (34)	15 (20)	60 (80)	50 (68)	45 (54)

A 469-04a Mechanical Properties

Property	Cl. 1	Cl. 2	Cl. 3	Cl. 4	Cl. 5	Cl. 6	Cl. 7	Cl. 8	Cl. 9
UTS ksi (MPa)	60 (415)	75 (515)	80 (550)	85 (585)	90 (620)	95 (655)	105 (725)	105 (725)	115 (795)
Yield ksi (MPa) 0.2 %	25 (170)	35 (240)	45 (310)	55 (380)	65 (450)	75 (515)	85 (585)	. . . . . .	. . . . . .
Yield ksi (MPa) 0.02 %	. . . . . .	. . . . . .	. . . . . .	. . . . . .	. . . . . .	. . . . . .	. . . . . .	85 (585)	95 (655)
E % Long Radial	25 18	22 18	20 16	20 15	18 14	17 13	16 10	16 11	14 9
RA % Long Radial	45 30	40 30	35 28	35 27	35 26	32 25	30 20	30 21	27 18

the change in this temperature with changing composition is quite startling. The nickel-chromium-molybdenum alloy steels were introduced into Specification A 469 for this purpose.

Vertical heat treatment is listed as the preferred method, and by the use of a supplementary requirement can be made mandatory. This heat treatment orientation has a great deal of influence on the control of distortion, both during normalizing and tempering and quenching and tempering cycles, and considerable development in furnace and quench facility design has been done to accommodate large rotor forgings.

In terms of the tension test requirements, it should be noted that Table 2 requires measuring the yield strength at an offset of 0.02 % rather than the 0.2 % offset measurement that is standard in ASTM A 370, Standard Test Methods and Definitions for Mechanical Testing of Steel Products. Provision is made for the yield strength to be measured at 0.2 % (at the purchaser's option?) in which case the minimum yield strength requirements for the applicable class are to be increased by 5 ksi (35 MPa).

As with the other ASTM rotor and disk specifications, the acceptance criteria for the nondestructive examinations are defined by the purchaser, and often depend on the type and location of any indications.

A 470-03, Vacuum-Treated Carbon and Alloy Steel Forgings for Turbine Rotors and Shafts

This specification covers both the high and low pressure steam turbine rotors, and like Specification A 469/A 469M has its origins in an Emergency Specification ES26 from the 1943 to 1946 period followed by Specification A 293 that was first published in 1946. Carbon steel rotor forgings are not now included, being unsuitable for the higher operating temperatures currently in use, and lacking the corrosion resistance of the martensitic stainless steels for applications involving lower pressure wet steam.

Vacuum degassing is mandatory, and in the situation where electroslag remelted ingots are specified, the primary heat must have been vacuum degassed. Supplementary Requirement S7 delves into additional requirements for consumable electrode remelted material, particularly the situation where successive electrodes are needed to provide sufficient material for the remelted ingot. This reflected the development of very large ESR furnaces intended to supply ingots for large rotor applications.

Basic electric steel making is specified as it has been since the specification was first published, and ladle refining is included in Specification A 788/A 788M.

Earlier revisions of Specification A 470 used the term Class to identify composition and mechanical properties. Currently, the term Grade applies to the chemical grouping and Class now applies only to the mechanical properties. The changes are shown in an appendix to the specification, so that it should not be necessary to revise older drawings and files.

The steel compositions include nickel-molybdenum-vanadium, chromium-molybdenum-vanadium, and nickel-chromium-molybdenum-vanadium alloys. Silicon is restricted to a maximum of 0.10 % and aluminum is limited to a maximum of 0.015 %. These limitations reflect the use of current ladle refining techniques. The older vacuum carbon deoxidation procedures are still permitted. In addition to the usual heat analysis results, the supplier must also determine a product analysis for each forging.

Temper embrittlement, as shown by an increase in the transition temperature and reduction in Charpy impact test absorbed energy, can be a problem for turbine rotors because of the time taken to cool from the temper and stress relief cycles, not to mention operating temperatures. This tends to be aggravated in large diameter forgings, and, for Grade C steps to reduce the incidence of this embrittlement by chemistry restrictions, notably on manganese and molybdenum, are included in Supplementary Requirement S4. This is in line with some published recommendations [6]. A step cooling test from 1100°F (595°C) is included in S4, and this involves holding Charpy test specimen material at a series of temperature steps totaling 160 h, in addition to furnace cooling time, down to 600°F (315°C), and then determining the FATT. In a similar vein, the purchaser may specify a J factor value determined from the heat analysis in accordance with Supplementary Requirement S24 of Specification A 788.

The need to keep the longitudinal ingot and forging axes together is an important item that is mentioned under the heading of the forging process. Failure to do this (for example, by uneven heating of the ingot for forging) can lead to rejection of the forging in the required heat indication test.

The heat treatment requirements are quite detailed in terms of the type of cycle, and in general terms for temperature (for example, in a double normalizing cycle) the first normalizing temperature must be significantly above the upper transformation temperature, while the second normalizing operation is to be done at a lower temperature. There is provision for including the initial normalize with the post forge heat treatment. This is useful in refining the grain size prior to an initial ultrasonic scan before the quality heat treatment. Minimum tempering temperatures are specified for the various grades. It should be noted that the temperature requirements for the final stress relieving heat treatment do have an effect on the tempering temperature for Grades A, B, C, and E. The minimum tempering temperature for these grades is 1075°F (580°C), and the minimum stress relieving temperature is 1025°F (550°C), a difference of 50°F (30°C). This must be remembered in the choice of the stress relieving tempering temperature. For example, if the tempering temperature is 1075°F (580°C), stress relieving temperatures of 1050°F (565°C) or higher will trigger additional mechanical testing.

Vertical heat treatment can be required by specifying Supplementary Requirement S 5.

The tension and Charpy impact test specimen locations are not defined in the specification, since these will depend on the design of the rotor, but generally axially oriented specimens are located in prolongations of the rotor journals, and radial specimens are located in the body portion. These test areas may be located outboard of the end rotor wheels or disks, and frequently when the design permits, from locations between the wheels. It will be readily recognized that the purchaser must supply a drawing to identify these locations with precision. Similarly, the forging supplier must take great care in removing the test blanks to avoid ruining the rotor. As noted in the generator rotor Specification A 469/A 469M, the yield strength requirement must be observed closely since the design may be based on an offset of 0.02 or 0.2 %. Minimum values for both of these situations are provided in Table 2, and both must be complied with since the specification states that the requirements of Table 2 are to be met.

Another aspect of the mechanical testing requirements is that they are intended to be complete before running the final stress relief heat treatment. One reason for this is that since the rotor is generally heat-treated as a solid cylinder, that is before the wheel stages are gashed, an appreciable amount of machining remains to be done after completion of the mechanical testing. However, there is the precautionary note, also addressed under heat treatment, about additional testing if the stress relief temperature is within T°F − 25 (T°C − 14) of the tempering temperature T.

Although ductility requirements are included for both longitudinal and radial tension test specimens, it should be noted that the Charpy impact test requirements apply only to radially oriented specimens.

An ultrasonic examination of the forging in accordance with Test Method A 418 is required. This is to be done after heat treatment and before removal of test specimens in locations that would interfere with the examination. The purchaser must provide the acceptance criteria.

Many rotor designs include an axial bore that is machined after heat-treatment, an example being shown in Fig. 18.1. Not infrequently a core is trepanned from the specified location and mechanical tests may be required from this material in accordance with Supplementary Requirement S2. The bore surfaces are to be examined visually, but magnetic particle examination of such bores is commonly required.

Not included in the specification because the purchaser, in most cases, does considerable machining after delivery of the forging, magnetic particle examination can be called for by the use of a supplementary requirement. It should be noted though that few, if any, forging suppliers would ship such a vital component without first examining the piece in accordance with Test Method A 275/A 275M.

A stability or heat indication test in accordance with Test Method A 472 is required for Grades D and E. Supplementary Requirement S11 provides for heat indication tests for any of the remaining grades. As previously discussed, this test is intended to expose any tendency for the rotor to warp during and after heating to the required temperature, generally at or slightly above the maximum operating temperature. A tendency for excessive run out can often be corrected by an additional stress relieving operation, and sometimes, with purchaser approval, the stress relief is included as an initial stage in the heat indication test. A forging whose axis does not correspond to the original ingot axis will probably fail this test.

A 471-94, Vacuum-Treated Alloy Steel Forgings for Turbine Rotor Disks and Wheels

This is the third of a group of four specifications, first published in 1962, that deals with generator and turbine rotor forgings. The fourth standard in the group is A 472, a test method for heat stability testing of steam turbine rotors. Like the preceding three specifications the requirement is for vacuum degassed alloy steel. The specification is currently under revision for conversion to the dual format and to reference the General Requirements Specification A 788.

Since the product takes the form of relatively flat, large diameter disks, a minimum upsetting requirement of 2:1 is specified, meaning that the axial length of the billet or preform before upsetting must be at least twice the axial height of the finished disk forging. As is the case for tube sheet forgings, in order to consolidate the axial center of the disk, it is necessary to do a certain amount of axial forging work on the billet before upsetting to form the disk.

The heat treatment requirement is for a normalize, quench, and temper cycle, where the initial normalize may be a part of the post forge heat treatment. Preliminary machining must be done before the quench and temper stage.

A minimum tempering temperature of 1100°F (595°C) applies for all classes except Class 10 when a minimum of 1200°F (650°C) is specified.

Post heat treatment stress relief is required if the stock removal, excluding the peripheral test material, exceeds 3⁄16 in. (5 mm). Minimum temperatures are specified for this operation, but there is no provision for retesting if the stress relieving temperature infringes on the 25°F (14°C) window under the tempering temperature.

A 768-95, Vacuum-Treated 12% Chromium Alloy Steel Forgings for Turbine Rotors and Shafts

First published in 1979, this rotor specification was written to cover the use of the martensitic stainless steels for turbine rotors, used both in the wet steam service typical of many nuclear power applications, and the advanced high temperature designs.

Use of the basic oxygen or open-hearth steel making processes is not allowed, but their application for these steels would not be economic in any case because of chromium losses. The more likely route would be by the electric furnace coupled with a ladle refining unit or an AOD converter if separate vacuum degassing facilities are available. For ESR ingots, the electrodes are required to have come from a vacuum degassed heat, and the need to maintain the ingot axis with the forging axis is stressed.

Four martensitic stainless steel alloys are included, three of which are available in a choice of two strength classes. The highest of these, Grade 2, has a minimum tensile strength of 150 ksi (1035 MPa), and a minimum yield strength of 110 ksi (760 MPa). This is higher than any of the alloy steels included in Specifications A 469, A 470, or A 471.

Considerable research activity, much of it involving the Electric Power Research Institute (EPRI) [7] and the European COST 501/502 [8] program, has centered on advanced 12 % chromium rotors and disks [9,10]; however, as yet none of these materials has been suggested for inclusion in this specification.

A 891-98, Precipitation Hardening Iron Base Superalloy Forgings for Turbine Rotor Disks and Wheels

This specification is an example of meeting the requirements for a specific application in the power generation industry. The forgings are intended for elevated temperature applications. The alloy formerly known under the UNS designation K66286 is now designated S66286 and is sometimes referred to by the trade name A286. This is nominally a 25 % nickel-15 % chromium-1¼ % molybdenum-2 % titanium stainless steel with boron and vanadium. The titanium addition contributes to the precipitation hardening effects in the γ' intermetallic compound, as well as protecting the boron used to enhance the creep strength of the material.

The steel is required to be vacuum melted followed by secondary melting by either the VAR or ESR process.

The heat treatment is described in some detail as a requirement for each of the two strength conditions (types) specified. In addition, stress rupture testing to ASTM Practice E 292 is required at 1200°F (650°C), as well as creep testing to Practice E 139 at 1000°F (540°C).

A companion grade of material, S66220 (known as Diskalloy) is used for similar applications but has not been suggested for inclusion in Specification A 891.

A 940-96, Vacuum Treated Steel Forgings, Alloy, Differentially Heat Treated, for Turbine Rotors

Because of steam temperature conditions the requirements for the high pressure (HP) rotor in a steam turbine differ from those needed in the intermediate pressure (IP) and low pressure stages (LP). Although the steam temperature may be the same in a design that uses an IP stage, through the use of a reheater stage in the boiler, in the LP stage both the temperature and pressure are lower. For a combined HP and LP or IP and LP rotor, the use of differential heat treatment enables good elevated temperature properties to be maintained in the high temperature stage, while enhanced toughness is obtained in the LP stage [11]. This is the purpose of Specification A 940.

Vacuum degassing is mandatory for the steel, and the only grade is a chromium-molybdenum vanadium alloy steel that does not have high toughness in the normalized and tempered condition used to obtain optimum creep strength.

The prescribed heat treatment for the HP section of the rotor is austenitizing fully followed by fast air-cooling. Although vertical heat treatment is not mandatory, this is usually achieved by placing the forging vertically in a cooling tower and using high capacity blowers to accelerate the air-cooling.

For the LP side of the rotor, the cooling from the same austenitizing temperature is achieved by water quenching using water sprays. It will be apparent that to do both heat treatment operations at the same time, the rotor must be suspended in the cooling tower with the LP section down for the spray quenching. The forging would be rotated during the cooling processes. Tempering is required at a minimum of 1200°F (650°C), and the same tempering temperature applies to both sections of the rotor.

Although the same tensile and yield strength and ductility requirements apply to both sections, the Charpy V-notch limits are very different. The HP section must meet a minimum of 6 ftlb (8 J) at room temperature and a maximum transition temperature of 250°F (120°C), while the requirement for the LP section is 25 ftlb (34 J) and a maximum transition temperature of 36°F (2°C).

A 982-00, Steel Forgings, Stainless, for Compressor and Turbine Airfoils

As is the case for Specification A 891, this specification was written for an important, specific component application in the power generation field. The airfoils can be produced as open die forgings, but since appreciable numbers of a given airfoil are normally required, closed or impression die forging would be favored.

Five of the six alloys that are currently included are 400 series martensitic stainless steels, and the sixth is the 17-4PH precipitation hardening martensitic stainless grade. Identification by UNS numbers is included.

The manufacturing requirements include a limitation of 2150°F (1175°C) for the maximum metal temperature during forging, and specific heat treatment requirements for each grade are described in a table. Since straightening after heat treatment is a distinct possibility, given the shape of compressor and turbine blades, a mandatory stress relieving heat treatment requirement following straightening is included in the table. Quenching from the stress relief temperature is not permitted, since this can lead to further distortion during subsequent machining.

A supplementary requirement, S1, mandating a secondary melting process is provided, together with another associated requirement, S2, requiring a heat analysis from each remelted ingot, rather than from one remelted ingot from a master heat.

Although the sulfur and phosphorous limits for Grades A, B, C, and D are appreciably lower than the requirements of most other martensitic stainless steel specifications, it is likely that significant further reductions, particularly for sulfur, would be required for best mechanical properties. This is particularly the case for Grades E and F. For example, the limits for sulfur and phosphorus are appreciably lower for the 17-4PH material in Specification A 579/A 579M as Grade 61 as compared to the requirements for these elements for 17-4PH as Grade F in Specification A 982. In addition, product analysis tolerances for sulfur and phosphorus are not permitted in Specification A 579/A 579M for Grade 61.

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Steel Forgings for General Industry

THIS GROUP OF SPECIFICATIONS COVERS A WIDE range of applications outside of the field of pressure vessels and power generation. Included are mechanical components such as gears and pinions, crankshafts, steel mill rolls and components for defense, railroads, and other applications that fall under the heading of "General Industrial." The specifications fall into two main categories, those with stated chemical compositions and those in which, because the size range is not defined, the manufacturer generally chooses the required composition under the broad headings of carbon or alloy steels in order to obtain the mechanical properties stated in the specification.

A 290-02, Carbon and Alloy Steel Forgings for Rings for Reduction Gears

This, one of the older ASTM steel standards, was first published just after the end of WWII in 1946. It covers an important type of forging used in many mechanical applications ranging from marine propulsion systems to earth moving equipment.

The steels used are considered to be weldable, under the proper conditions, and in this respect it should be realized that the carbon levels will substantially exceed 0.35 % in most cases.

It should be noted that the rings can be ordered either to mandatory mechanical properties including tension, impact, and hardness tests, or simply to a hardness range. This is defined by the class designation for the required grade, and so is an important item in the purchase order.

Depending on the required ring dimensions, the forgings could be produced on a ring-rolling machine, or as rings produced as hollow forgings on a press. If the quantities required permit, then the rings could be made from a multiple forging and separated before or after heat treatment; in the former case the surface hardness of the end faces could pose a problem.

Nondestructive examinations are not specified, although supplementary requirements for this purpose are provided in the specification as well as in Specification A 788. Possibly because cutting the gear teeth (a highly specialized operation) would not normally be done by the forge shop, a surface NDE was not included as a specification requirement. An ultrasonic examination would, however, be desirable, given the cost and importance of such components.

The use of the hardness only option should be weighed carefully. The mechanical testing option, given the number of tests and that it involves the use of an integral full section test prolongation, gives full assurance that the required properties have been obtained in the forging. The specification requires that hardness testing be done after final machining to the ordered dimensions. This testing is specified for the flat end faces of the ring at stated locations, and the number of impressions required increases with the ring diameter, so that uniformity on the surface can be assured. However, depending on the grade selected and the cross section of the ring, the hardness may reduce moving into the cross section, so that the gear tooth root area may be softer than expected.

The carbon ranges for all of the grades are wide enough to permit the selection of a carbon level suitable for surface hardening by flame or induction methods.

Vacuum degassing is not a specification requirement, but would be advisable for the steels concerned, and can be included in the purchase order by means of a supplementary requirement, chosen from Specifications A 788 or A 290. Two similar carbon steels, Grades A and B are included, with Grade B having a restricted carbon range of 0.40–0.50 % and a higher tensile strength. The manganese to carbon ratios possible with these steels are quite low, being of the order of 2:1, and this can adversely affect notch toughness; however, these steels do fall in line with popular grades, such as SAE 1040 and 1045. It should be noted that the carbon steel grades carry limits on the common alloying elements, probably to exercise some control over weldability.

The Grade 3 alloy steel has a carbon range of 0.35–0.45 %, so that it embraces SAE 4140.

Grade 4 is a nickel-chromium-molybdenum alloy with a wide carbon range that permits three strength classes. The SAE Grade 4340 could be accommodated in Grade 4, as well as some of the popular variants with higher molybdenum contents. Grade 6 is similar to Grade 4, except that the nickel and molybdenum ranges are higher, and a vanadium range is specified. This material would accommodate through hardening of thick ring sections.

The last alloy steel, Grade 5, is one of the Nitralloy steels with a nominal 1 % aluminum that would provide a very high hardness case for the gear teeth after nitriding.

Perhaps as a reflection on the size of gear rings produced to this specification no carburizing steels are included.

Heat treatment is prescribed for all grades, either by normalizing and tempering for both classes of Grade 1, or quenching and tempering for all of the other grades and classes. Minimum tempering temperatures are laid down also. Unless the material has a very fine grain size, normalized and tempered forgings to Grade 1, Class 1 may be marginal for the required Charpy impact test. This should not be a problem for the remaining grades since they are required to be quenched and tempered.

The mechanical testing requirements are explicit using integral test prolongations. These are to be extensions of the length of the ring, and one prolongation is required for each forged ring; or if gear rings are forged in multiple to be separated after heat treatment, one prolongation is required at the end of each multiple. Heat lot testing is not permitted. Two tension tests and two sets of Charpy impact specimens are required from each test prolongation. These are to be offset 180° from each other and oriented tangentially to the ring diameter. This, in effect, would be parallel to the direction of maximum hot working for a ring forging.

It should be noted that the Charpy impact test requirement in Table 2 is not listed as being an average value so that each specimen is required to meet the minimum absorbed energy requirement.

A 291-03, Steel Forgings, Carbon and Alloy, for Pinions, Gears, and Shafts for Reduction Gears

A companion to Specification A 290, this specification was first published in 1946 and is intended for power transmission gearing for marine and other transport and mechanical applications. As opposed to Specification A 290 the forgings here are intended to be cylindrical rather than rings. Although the carbon contents involved tend to be high, the steels used are considered to be weldable, provided that the appropriate precautions are taken.

The materials involved are very similar to those in Specification A 290, including a carbon steel with limited alloying elements, a carbon/alloy steel in which by agreement nickel, chromium, and molybdenum can be added, a chromium-molybdenum alloy, three nickel-chromium-molybdenum steels and a nitriding grade.

Carbon contents can range as high as 0.55 %, and although for Grades 2 through 3A carburizing is possible because only a maximum carbon is specified and a quench and temper heat treatment is specified, it would seem that any local hardening of gear teeth is intended to be limited to induction or flame hardening or nitriding.

The silicon requirement is listed as a maximum of 0.35 or 0.40 % for all grades so that low silicon steels produced during ladle refining as well as by vacuum carbon deoxidation can be accommodated. It should be noted that the General Requirements Specification A 788/A 788M requires that the steel used be killed.

No provision is made for using separate test bars for mechanical testing, so that the necessary material must be provided as an extension or prolongation of the main body (where the gear teeth will be located) from each forging. Special conditions apply for gears that are forged as multiples, or for those weighing less than 500 lb (225 kg).

A feature of the specification is that, for the larger diameters, provision is made for both longitudinal and tangential orientation of the test specimens. This choice is at the producer's option and reduced ductility values are permitted for the tangential orientation. This distinction is carried forward to the optional Charpy impact tests that are covered by Supplementary Requirement S2, although of course these are done only when specified in the purchase order.

Like Specification A 290, surface hardness ranges are specified for each strength class; however, a restricted hardness range for a given forging within the prescribed limits is not included.

As is the case with Specification A 290, mandatory nondestructive examination is not a specification requirement. Again, in the case of a surface examination, this would normally be done on the finished shape with the gear teeth formed, but the forging producer would be well advised to do both a volumetric and a surface examination on the heat treated blank, since a later claim may include machining costs incurred after delivery.

A 427-02, Wrought Alloy Steel Rolls for Cold and Hot Reduction

First published in 1958, Specification A 427 is an example of an ASTM forging specification written for a specific industry application. The specification is short and does not include specific steel composition requirements. This aspect is left to the forging supplier unless included in the purchase order.

Surface hardness is an important property of steel mill rolls, and traditionally, this has been done using rebound hardness testers such as the Scleroscope in which a hardened tup is dropped onto the roll surface and the hardness measured in terms of the height of the rebound. Although rebound hardness testing is widely used industrially for a variety of products, particularly if they are hard, Specification A 427 is unique in specifying it as a required test practice. The Scleroscope was the original hardness-testing instrument referenced in Specification A 427, and this requires a practiced eye to take the hardness readings in one of the Shore scales from Test Practice E 448, Scleroscope Hardness Testing of Metallic Materials.

Hardness testing using Test Method A 956 is now included in the specification, since instrumented rebound hardness testers using the Leeb principle have been found to be particularly useful in hardness testing this type of forging.

A 504/A 504M-04,$^{\epsilon 1}$ Wrought Carbon Steel Wheels

This specification was first published in 1964, replacing two earlier specifications, namely Specification A 57, Multiple Wear Wrought Steel Wheels, and A 186, One Wear Wrought Steel Wheels. Specification A 25, Wrought Steel Wheels for Electric Railway Service was incorporated in Specification A 504 in 1993. In the current revision, the specification was extensively revised to incorporate Specification A 788 and change to the dual format. Although perhaps not obvious from the title, the scope clause indicates clearly that this specification deals with wheels for locomotives and rolling stock for the railroad system, and certain terms such as one wear, multiple wear, and tape size are described in the definition of terms section.

It should be noted that, in the United States, forgings for wheels and axles besides complying with specification requirements are approved on a prototype basis by testing carried out at the AAR facilities in Pueblo, Colorado.

Four classes of carbon steel are included. These vary in carbon content, and would be classified as medium to high carbon steels.

The wheel forgings are heat treated by first austenitizing and then quenching to harden the rims or running surface, followed by tempering to obtain a rim surface hardness within the range specified for the ordered class. These hardness ranges vary in width from 40 to 80 Brinell points.

Ultrasonic examination is still required, but now must conform to Practice A 388/A 388M. Scanning and calibration requirements are included in the specification. Magnetic particle examination using the wet fluorescent method in accordance with Test Method A 275/A 275M is required, and a basic set of acceptance criteria (that can be amended by the purchase order) is now included.

Shot peening of what is called the plate surface, located between the wheel hub and rim, is a requirement. This is intended to improve fatigue strength of the wheel.

Specific marking requirements are a part of the specification.

A 521/A 521M-04, Steel, Closed-Impression Die Forgings for General Industrial Use

This is the single ASTM forging specification that addresses impression or closed die forgings directly. It includes both carbon and alloy steels and a range of heat treatment options. Since impression or closed die forgings are normally produced in some volume, the choice of steel is a purchase order item, together with the strength grade required. The producer, before accepting an order, should concur that the chosen carbon or alloy steel will be capable of meeting the required tensile strength requirements when processed according to the specification.

For Grade CA forgings the purchaser may specify that one tension test per heat be taken. While no tensile requirements are specified, the purchaser may wish to know what the as forged tensile properties are for the forging in question, so that if needed, heat treatment could be done.

The supplementary requirements include one, S2, on grain flow. This enables the purchaser to evaluate the grain flow obtained relative to the intended service. This could be useful in the development of prototype components.

The specification has extensive nonmandatory appendices on forging and die tolerances that can be specified by the purchaser through the purchase order.

A 551-94, Steel Tires

This specification for carbon steel tires for railway locomotives and rolling stock was first written in 1965 to replace two earlier specifications, A 26 and A 329. The major difference between these two older specifications was that for A 329 the forged tire rings had to be quenched and tempered, whereas heat treatment was not specified for A 26. The specification is somewhat dated, does not reference Specification A 788, and is currently under revision.

Although manufacture is not actually mentioned, the tires would be produced, close to the required size and shape, as forged rings. The materials specified are medium to high carbon steels, but there is an option for the purchaser to specify additional alloying elements.

Hardness ranges are provided for the heat-treated classes, but tension testing is provided only by supplementary requirement.

A 579/A 579M-04a, Superstrength Alloy Steel Forgings

Originally published in 1967, this specification includes a large number of high strength special alloy and stainless steels that had been developed to meet various applications, both commercial and military, that call for tensile strengths generally of 150 ksi (1035 MPa) or above. An example of a military application for Grade 84 is shown in Fig. 19.1.

The compositions listed in the chemical requirement table range from a mundane SAE 4130 alloy with a specified vanadium range to the far more complex maraging steels. The steels are identified by a grade numbering system that currently starts at Grade 11 and runs to Grade 84 with many gaps. The rationale for the numbering system is not clear, but it is presented best in the table of tensile properties where the grouping is shown according to heat treatment. Many of the steels were proprietary at one time, with readily recognized trade names, and some may have had patent protection; however, this is not currently the case.

The included alloys all have UNS designations, and these together with some of the names by which they were known are included in the following table.

Grade	UNS Number	Common Name
11	K42598	3Ni1.5Cr0.9MoCb Gun steel type
12	K51255	HY130
12a	K51255	HY140
13	K13051	SAE 4130 + 0.05-0.10V
21	K23477	Nonstandard 4300 series: 4335Mo
22	K24070	SAE 4340 with increased molybdenum
23	K24728	D6a (D6ac if VAR used)
31	K32550	High silicon, nickel, chromium, molybdenum
32	K44220	High silicon, nickel, chromium, molybdenum
33	K14394	High silicon, chromium, molybdenum
41	T20811	H11 Tool steel
51	S41001	Martensitic stainless steel, Type 410
52	S42201	Martensitic stainless steel, Type 422
53	S43100	Martensitic stainless steel, Type 431
61	S35000	Precipitation hardening semi-austenitic: AM350
62	S17700	Precipitation hardening semi-austenitic: 17-7PH
63	S43100	Martensitic stainless steel, Type 431
64	S35500	Precipitation hardening semi-austenitic: AM355
71	K92820	Maraging steel (200)
72	K92940	Maraging steel (250)
73	K93120	Maraging steel (275)
74	K91930	Maraging steel, 12-5-3 (160)
75	K91940	Maraging steel, 12-5-3 (180)
81	K91122	9 Nickel-4 Cobalt steel: HP9-4-25
82	K91283	9 Nickel-4Cobalt steel: HP9-4-30
83	K91094	9 Nickel-4 Cobalt steel:
84	K91472	9 Nickel-4 cobalt steel: HP9-4-20

The heat-treated cross-sectional limitations in the use of these alloys are indicated relative to minimum yield strength by means of a table. This indicates, as would be expected, that Grade 13 (SAE 4130) has a maximum heat treated section size of 1 in. (25 mm) when yield strengths up to 180 ksi (1240 MPa) are required; however, it should be noted that the room temperature Charpy V-notch requirement at room temperature drops from a minimum of 20 ft-lbf (27 J) for

Fig. 19.1—A guided 5000 lb (2265 kg) penetrator warhead being dropped at a test range. The warhead was forged from a high strength low alloy steel with a composition similar to Grade 84 of ASTM A 579/A 579M.

the 140 ksi (965 MPa) minimum yield strength to a minimum of 10 ft-lbf (14 J) when a minimum yield strength of 160 ksi (1100 MPa) is required. It should be noted too that no minimum tempering temperatures are specified.

Many of the alloys included in this specification were intended to be remelted in order to maintain acceptable ductility and toughness. The advent of ladle refining has reduced this need in many cases, but it should be stressed that clean steel practices are most important to the successful application of this specification, and easy machinability should not be expected.

Acceptance criteria for the mandatory nondestructive examinations is not included, since these depend on the forging application, but reference is made to the supplementary requirements of Specification A 788 to assist the purchaser.

A 646/A 646M-04, Premium Quality Alloy Steel Blooms and Billets for Aircraft and Aerospace Forgings

Originally published in 1971, this specification saw a major revision and conversion to the dual format in 2004. The product is for hot worked starting stock for forgings, and requirements for minimum hot working cross section reduction are based on the required area of the bloom. It is noted in the scope that the terms billet and bloom are regarded as being synonymous. The purchaser of billets or blooms to this specification would normally be a forging producer rather than an end user.

The specification was originally written to include two classes, one for remelted material and the other for vacuum degassed electric furnace steel that was teemed either in air, or under vacuum. This was augmented, at the time that the specification was updated, to include a third class of steel that was vacuum degassed and ladle refined. This new class, although intended to be intermediate between the existing Classes 1 and 2 in terms of quality, was numbered as Class 3. This was to avoid any confusion for users of the earlier revisions of the specification.

The commonly used steel cleanliness standards in the aerospace industry are AMS 2300 and AMS 2301 [1], and reference to these is included in a supplementary requirement. With the advent of secondary ladle refining a third standard AMS 2304 [1] was introduced and this also is now included in the supplementary requirement. It should be noted that steel cleanliness is still required to be rated in accordance with Methods E 45, Determining the Inclusion Content of Steel, even if Supplementary Requirement S1, Magnetic Particle Cleanliness, is specified in the purchase order; however, the purchaser is required to specify the acceptance criteria.

A companion specification, Test Method A 604, covers the macro etch testing of carbon and alloy steel bars, billets, and blooms produced from consumable remelted ingots. For the vacuum degassed air melted steel of Classes 2 and 3, the requirements of ASTM E 381, Method for Macroetch Testing, Inspection, and Rating Steel Products, Comprising Bars, Billets and Blooms, and Forgings, apply. Again for Methods E 381 and A 604, the acceptance criteria must be furnished by the purchaser, who in most cases would be the forging producer. It follows that the requirements for the end user must be available to the bloom or billet producer.

Volumetric quality by ultrasonic examination is another mandatory part of the specification. This may be by the contact method in accordance with Practice A 388/A 388M, or by the immersion method in accordance with Practice E 214, Immersed Ultrasonic Examination by the Reflection Method Using Pulsed Longitudinal Waves.

Another feature of the specification is the provision of a chemical composition table for an assortment of alloys that have been commonly supplied for aerospace forging application. These include some of the materials, including 4130, found in Specification A 579; however, the grade numbers do not coincide. It is noted that the material listing provided is not intended to exclude others that could be provided under this specification.

A 668/A 668M-04, Steel Forgings, Carbon and Alloy for General Industrial Use

This widely used specification was first published in 1972 as a result of the merging of three earlier specifications from the 1940–1942 period. These were:

- A 235, Carbon Steel Forgings for General Industrial Use
- A 237, Alloy Steel Forgings for General Use
- A 243, Carbon and Alloy Steel Ring and Disk Forgings

It is not unusual for older drawings to reference one of the original specifications, and a table is included as an appendix to Specification A 668/A 668M, showing the relationship between the older specifications and the new combined specification.

The specification includes two steel categories, carbon and alloy, with the separation based on strength level. The individual grades are distinguished by heat treatment type and by strength or hardness level. Another most important aspect of the specification is that there are essentially two situations:

The first involves forgings that are required to be tension tested and the minimum requirements are based on the heat-treated section size.

The second is for forgings that are ordered to a hardness requirement only.

The distinction between these options is that the hardness only situation requires certification and marking with the suffix "H." For example, forgings ordered to Grade F, meaning carbon steel in the quenched and tempered or normalized, quenched and tempered condition with specified minimum tensile properties and hardness would be certified and marked as Grade F. The same forging with the same heat treatment, but only hardness tested, would be certified and marked as Grade FH. Forgings in the as forged condition, that is supplied without heat treatment, are covered only as carbon steels, Grades A or AH. All of the remaining conditions Grades B/BH through N/NH must be heat treated as prescribed for the particular grade.

Carbon steels are covered by Grades A through F.

Grades G through N are required to be alloy steels.

Because the application of the forgings supplied to Specification A 668/A 668M is so diverse, the choice of steel is intended to be left to the manufacturer, the purchaser stipulating the desired Grade and whether or not tension testing is required. It should be noted, however, that provision has been made for the purchaser to include the choice of steel composition, and an appendix to the specification gives examples of some standard steel compositions that are used when making forgings to the various grades.

A feature of the specification that has been hotly debated is the chemical requirements table. This lists only maximum limits for manganese, phosphorus, and sulfur for the carbon steels and phosphorus and sulfur for the alloy steels. Through reference to the General Requirements Specification A 788 and from there to the Terminology Specification A 941, one arrives at a definition for an alloy steel, but the purchaser should be aware that the supplier may attempt to use a carbon steel when an alloy steel is required.

The intended purchaser is always advised to request that the proposed steel chemistry or standard chemistry designation be furnished when considering buying a forging to this specification.

When tension testing is required, the details for the number and location of specimens are given in detail. Hardness testing locations and number of tests are specified, as well as specific restrictions on the variation in hardness within the allowable range.

It is important to note that the specification does not include Charpy impact testing, although that may be accomplished by reference to the supplementary requirements in Specification A 788. However, the type of heat treatment used is of more importance when impact testing is ordered.

The provision for permitting forgings to be purchased on the basis of hardness testing only could amount to considerable cost savings because, apart from the cost of the test, there would be no need to provide test material. Depending on the application and forging size and type, the knowledgeable purchaser could use this to good effect, but in such a case appreciation of the capabilities of the proposed steel composition, the heat treatment cycle, and the heat treatment facility is essential. Responsible supervision would be desirable also.

Specification A 668/A 668M is used by many government agencies, both state and federal, for items as diverse as lock gate equipment and bridge parts to crane lifting hooks and support forgings for pressure vessels. It has a lot of potential if used properly, but is also open to abuse if the purchaser does not pay heed to the ordering requirements and the required certification. This should be remembered when comparing quotations for forged components to this specification.

A 711/A 711M-04, Steel Forging Stock

Similar to Specification A 646/A 646M, this specification deals with the raw material for making steel forgings. However, unlike the former specification, cast material such as ingots and strand cast shapes is included. Again in contrast to Specification A 646/A 646M, the terms "billet" and "bloom," as well as "slab," are defined in terms of cross-sectional area, but it is noted that the terms "billet" and "bloom" are frequently used interchangeably.

A requirement for a minimum hot working reduction of 2:1 is applicable to billets and blooms; however, the purchaser should be aware that these terms can be used for strand cast shapes, which are produced without hot working. This issue has been addressed in Specification A 788, whereby as cast shapes must be classified as cast billets or cast blooms.

Because of its more general application, unlike Specification A 646/A 646M, a list of commonly used steels is not included. Reference to Specification A 29/A 29M, Steel Bars, Carbon and Alloy, Hot-Wrought and Cold-Finished, General Requirements for, is used to assist in this choice.

Surface condition is often considered to be important in forging stock, and provision is made for local removal of defects or imperfections. This includes dimensional limits tied to the size of the stock. This subject is of particular importance for closed or impression die forgings.

A large number of supplementary requirements is provided to include such topics as hot working reduction, product analysis, macro etching, heat treatment tests, and nondestructive examinations.

The specification is intended for use by forging shops purchasing stock from a steel mill or warehouse, and some knowledge of ingots and wrought blooms and billets is assumed.

A 729/A 729M-05, Alloy Steel Axles, Heat-Treated, for Mass Transit and Electric Railway Service

Now in dual format this recently updated specification is intended to serve the needs of the railroad industry. All axles are now required to be heat treated, removing the variability associated with forgings in the as forged condition.

One of the important upgrades relates to the ultrasonic examination requirements where reference is made to Practice A 388/A 388M for the equipment and procedures, and references to obsolete equipment removed. Also Test Method A 275/A 275M is referenced for magnetic particle examination, and the mandatory Annex A1 is referenced for acceptance criteria. This annex was always mandatory but apparently was intended for visual examination. This revision, in calling for magnetic particle examination, makes the annex more effective.

The heat-treated Grades F, G, and H although classed as alloy steels had few chemical requirements. These grades are retained for continuity with the AAR requirements, but a report of the actual composition used is now required for the mandatory certification, since certification is now mandatory. New alloy steel Grades A, B, C, and D are included with full chemical requirements for the benefit of both producers and purchasers. The original strength requirements have been retained.

Two new interesting supplementary requirements are included, one on the use of quenching from a subcritical temperature above 900°F (480°C) to induce favorable residual surface compressive stresses [2], and the other for the measurement of residual stresses by X-ray diffraction.

A 837/A837M-03, Steel Forgings, Alloy for Carburizing Applications

This is one of the few specifications for steel forgings that do not include a table of mechanical properties. An understanding of the application explains this, since for carburizing applications the forging must first be machined close to its final form before being carburized over the designated surfaces, after which it is quenched and lightly tempered. As well as core material properties, the hardness of the carburized surface must fall into the required range. The machining, carburizing, and heat treatment would often be done in facilities removed from the forging producer, limiting the requirements needed for certification of the initial forging.

A blank carburizing cycle on a test bar could be used to qualify a heat for the core properties, and this could be a candidate for a new, as yet unwritten, supplementary requirement.

Post forge heat treatment by normalizing or normalizing and tempering is mandatory, and a maximum hardness requirement of 229HB applies regardless of composition. This is intended to help machinability.

Typically for carburizing application, the carbon content of the base material is restricted to less than 0.25 %.

A 909-03, Steel Forgings, Microalloy, for General Industrial Use

Representing an important group of forging materials that have become very important in the automotive and construction equipment industries, Specification A 909 is closely allied to the bar Specification A 576, Steel Bars, Carbon, Hot-Wrought Special Quality, that serves the same industries. Specification A 921/A 921M, Steel Bars, Microalloy, Hot-Wrought, Special Quality for Subsequent Hot Forging, is intended to be used in specifying the starting stock for forgings to this specification.

The basis of these steels is the ability to meet specified properties with no heat treatment beyond cooling after completion of forging. In this sense, to ensure reproducible results, it is important for a forging procedure, including the forging temperature range, to be established and adhered to. For this reason, the purchaser may request a written forging procedure. This is something to be considered seriously, given that the typical forgings will be relatively small and only two tension tests are required per heat or forging lot. The lot size definition, according to the terminology section, forms a part of the microalloy forge procedure, lending even more importance to this document.

A microstructure requirement of either a minimum of 90 % ferrite and pearlite or 90 % bainite forms a part of the metallurgical requirements. The frequency of establishing this is not specified, but tying this to the minimum tension test frequency would not be unreasonable.

It will be appreciated that for a process of this type that the cross-sectional dimensions of the forging will be a limiting feature, and the specification states that the maximum cross-sectional thickness or diameter is 4 in. (200 mm).

As an exception to Specification A 788/A 788M, this is the only forging product specification that requires the purchaser to request certification if this is required.

A 983/A 983M-04, Continuous Grain Flow Forged Carbon and Alloy Steel Crankshafts for Medium Speed Diesel Engines

Before dealing with this specification a few words concerning the development of this type of crankshaft may be helpful.

Besides being used in reciprocating internal combustion engines, crankshafts are found in some compressors, particularly those used in natural gas transmission service, and in mechanical presses.

For small quantity production and for low speed diesel engine use, slab forged crankshafts, made to a general application specification such as Specification A 668/A 668M, have been used frequently. For these applications, Specifications A 456/A 456M and A 503/A 503M can be used to specify nondestructive examination requirements and indirectly influence the forging production.

The advent of the medium speed diesel engine, with its more demanding crankshaft loading, opened wide applications in marine and land transport and, particularly when coupled with waste heat recovery systems, for electrical power generation systems. The success of these engines, multiplied by their conversion to natural gas for fuel, resulted in a need for improved forging quality and increased production capabilities, qualities that can be satisfied by the use of continuous grain flow (CGF) forgings [3].

Continuous grain flow crankshaft forgings can be produced as conventional closed or impression die forgings, and although size limitations are imposed by press capacity and die size, some locomotive crankshafts with crankpin or main bearing journal diameters of about 7 in. (175 mm) have been made this way. One V-16 locomotive engine design employed two such four throw crankshaft forgings bolted together by means of central flanges. From the repair and reconditioning aspect, this design permitted either the front or back half to be replaced.

Another limitation for large crankshafts made as single operation closed die forgings, close to the press power limits, was the need to hot twist to get the correct angular orientation for the crankpins.

A more versatile continuous grain flow forging process consists of building up the forging in a series of forging steps, using closed dies in either a specially designed multi-directional forging press, or using proprietary mechanical equipment under a conventional open die forging press, to amplify and convert by means of lever systems, the downward effort of the press to a horizontal force. For the latter, one system was developed in France and is known as the RR system [4]; another well-documented system was developed in Poznan, Poland by Dr. Tadeusz Rut and is known as the TR method [5]. These CGF crankshafts are sometimes referred to as staged or built-up crankshafts, but the latter term is used also for some very large low speed marine crankshaft designs where separate webs are shrink fitted onto the main bearing sections.

The CGF designs are produced in several countries using open die forging presses with additional equipment, but in the United States they are produced on one of two multi-directional hydraulic presses that were designed specifically to produce CGF crankshafts. One of these presses is shown in Fig. 19.2.

The heat to forge operation for these dedicated presses is done using induction furnaces, as illustrated in Fig. 19.3 so that only the area to be forged can be brought up to temperature quickly. The perils involved in using induction heating that were described in Chapter 6 must be recognized and taken into account for successful forging. One such problem is that the starting bar size for many medium speed diesel engines will exceed 7 in. (175 mm), and for the multi-directional presses can be as large as 11 in. (275 mm). The direct heating effect in a low frequency induction furnace is limited to the first 2 or 3 in. (50 or 75 mm) from the surface, so that the core of the bar is heated by conduction. If power is maintained until the center is up to temperature, the risk of overheating the surface is very high, so that a soak period with little or no power application is required.

The great advantage of the staged CGF forged crankshaft over the single closed die forgings, besides accommodating larger diameters, is that longer length one piece shafts are possible, and since the correct angular crankpin position can be maintained, hot twisting is eliminated. This facilitates the production of the large V-18 engines that are now popular for many marine applications.

The multidirectional presses enable forgings to be produced with minimal excess stock and facilitate the use of counterweights attached by welding, a technique that is popular with North American engine builders as well as some in Europe. The open die forging machine systems require additional excess stock for machining so that welded counterweights can be used only after additional machining. This may account for the continued prevalence of bolted counterweights used in most European engine designs.

Specification A 983/A 983M was written to provide a national consensus standard for a specific type of crankshaft that is in wide international use, and to replace or augment the many proprietary or in-house specifications written by engine builders. The specification permits the engine purchaser not only to have a say in the integrity of a vital component by referencing the specification in the purchase order for the engine, but to have a say, through the consensus standards process, in the contents of the specification.

Vacuum degassed steel is a specification requirement. Although hot rolled bar is an acceptable starting form for the crankshaft forgings, an important provision is that the

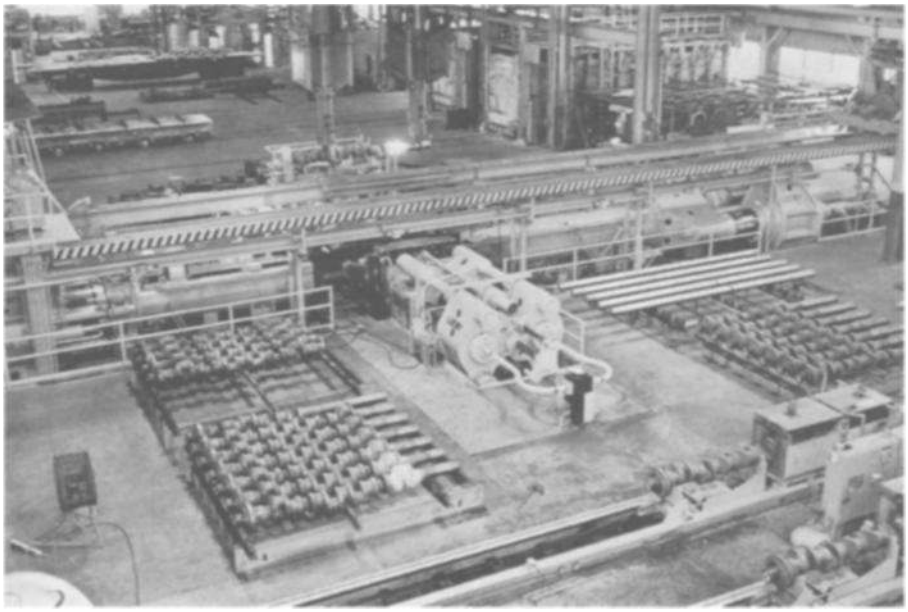

Fig. 19.2—A large multi-directional hydraulic forging press designed to make continuous grain flow crankshafts. The bars are heated in the two induction furnaces in the foreground and are carried to the closed die press by a special stiff leg crane. A partially completed crankshaft is being lifted from the press after forging a crankpin, and will join other shafts on the racks to the left and right of the press. Some new bars await the start of the forging process on the rack to the right of the press. The crankshafts are forged incrementally starting with the coupling flange and proceeding one crankpin throw at a time. Two gas fired horizontal furnaces used for final heat treatment are visible in the background. (Courtesy Ellwood National Crankshaft Company)

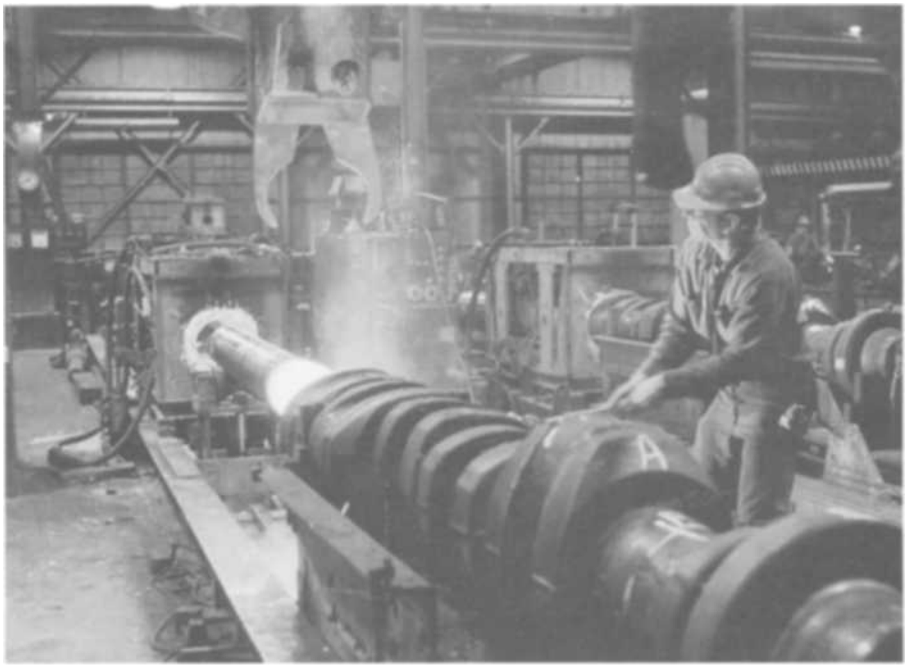

Fig. 19.3—A partially completed crankshaft forging being removed from an induction heating furnace for transfer to the closed die forging press. (Courtesy Ellwood National Crankshaft Company)

bar may not be produced by slitting a rectangular section, since this may defeat a prime advantage of continuous grain flow forgings in that the central core material from the original cast stock would be exposed on the surface. Initial preproduction or first article macro etch testing of the forging is required to demonstrate satisfactory continuous grain flow. Heat treatment is mandatory, and designs that include welded counterweights are addressed.

A grain size determination at the tension test location is required, and provision has been made for elongation to be measured on a 4D gage length for forgings made to inch-pound units and 5D when SI units are specified. This is one of the few ASTM product specifications to require the use of the 5D gage length for the tension test when SI units are required.

Charpy V-notch impact testing is included as a supplementary requirement since this is a necessary test for some marine inspection agencies. Many engineers would argue that impact testing is unnecessary for crankshafts, because the failure mode will either be by fatigue or mechanical heat damage to bearing surfaces through seizure.

The single most important nondestructive examination for crankshafts is by the magnetic particle method, because the primary failure mode is by fatigue that is strongly influenced by surface conditions in terms of metallurgical and mechanical effects. For this reason, the examination requirements are included in Specification A 986/A 986M that was discussed in conjunction with the test methods standards.

Ultrasonic examination is also covered in supplementary requirement and references Specification A 503/A 503M. The starting bar can be subjected to a full volumetric examination, but examination of the forging is more restricted because of geometric considerations. The examination should be done after heat treatment, but before drilling oil passages. Great care must be taken to eliminate misleading reflections caused by the complex geometry of the forging.

Although not common at present for marine crankshafts, surface treatment by nitriding or induction hardening is widely used for locomotive applications. Provision for this is included in the supplementary requirement section.

Two inclusion-rating provisions are also available as supplementary requirements. One of these covers conventional testing at the mid-radius position of the starting bar, and the second addresses the near surface location that is of great importance in the crankpin and main bearing positions.

A 1021-02, Martensitic Stainless Steel Forgings and Forging Stock for High Temperature Service

As the title suggests, a major application for the billets and forgings to this specification is the power generation field, and the included materials are found in Specification A 982/A 982M for turbine blade applications, although there is no cross-reference at this time.

The standard is unusual in providing for both stock for reforging and finished forgings.

The tension and impact test requirements mirror those in Specification A 982/A 982M, except of course for the 17-4PH stainless steel found in that specification. The Charpy V-notch impact test requirements for Grade D Class 1(UNS42225) are quite low, being on the lower shelf at room temperature.

It should be noted that a stress relieving heat treatment is required after straightening a forging, and that liquid quenching after stress relief is not permitted.

References

[1] AMS 2300/2301 and AMS 2304 from Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, PA 15096.

[2] Woodbury, C., III, Pearson, J., Downs, W., and Brandimarte, G., "Effects of Service on Residual Stresses in Sub-Critically Quenched Rail Car Axels," *ASME International RTD—Vol. 11—Rail Transportation Book G01031*, 1966.

[3] Nisbett, E. and Antos, D., "Manufacturing and Properties of Continuous Grain Flow Crankshafts for Locomotive and Power Generation Diesel Engines," *Steel Forgings, Vol. 2, ASTM STP 1259*, pp. 129–147.

[4] Ruget, G., "Development of the RR Continuous Grain Flow Process for Crankshafts," *The 5th International Forgemasters Meeting*, Terni, Italy, May 1970, pp. 503–520.

[5] Rut, T., "Forging of Long Stroke Crankshafts by the TR Method," *Steel Forgings, ASTM STP 903*, Nisbett and Melilli, Eds., pp. 504–519.

20

The Role of the Purchaser

AS WITH MANY OTHER COMMODITIES FORGINGS are produced to meet a particular need and in most organizations forging procurement is handled by a purchasing department. This group is expected to deal with all the materials, equipment, and components that are required to meet the manufacturing needs of the organization. The purchasing agent is the crucial link between the producer and the user. The purchase order (PO) is the vehicle used to convey the user's needs to the forging supplier, but before a purchase order is issued the purchaser needs to know that the material can be supplied, what it will cost, and when it can be supplied. This is usually achieved by asking for a quotation from one or more potential vendors. In U.S. Government parlance, such documents are known variously as an invitation for bid (IFB), request for proposal (RFP), or a request for quotation (RFQ). The RFP and the purchase order should be essentially the same at the very least in technical content. There may be several steps in this path and more than one purchasing entity may be involved. Quotation requests are often made to support an industrial exercise intended to confirm the feasibility of a design project and may never result in an actual purchase, but in any event the RFP should mirror as closely as possible the eventual purchase order, but taking into account changes that are the result of comments or exceptions taken by the selected supplier. Even in the apparently simple situation of the purchase of a fully completed forging, such as a forged crankshaft for a diesel locomotive from an integrated forging company, although the order for the crankshaft is placed directly from the engine builder to the manufacturer, the forge shop has to purchase materials to make the steel and the forging, as well as supplies such as nuts and bolts and oil hole plugs. From this then it is clear that not only are the request for pricing and the purchase order an indispensable part of the transaction, but the specification(s) that the forgings are made to become of major importance as well.

These specifications could be quite simple and contained within the quotation request and purchase order themselves, for example, a rolled steel bar 10 in. (250 mm) in diameter and 12 ft (360 cm) long to SAE 1045. This describes the size of the bar, its chemistry, and its condition. It is important to note here that the former, and still commonly used, AISI designations have been out of use for many years. This simple example quoted tells nothing about surface finish, dimensional tolerances, heat treatment, mechanical properties, or soundness of the material.

Perhaps some of the quotations received in response to this request would include some additional description of the required material, for example, that the bar would be hot rolled to mill tolerances on diameter and straightness, cut to length to a tolerance of −0, +0.25 in. (+6 mm), and with sawn ends. The material would be in the as rolled condition. There possibly would be no mention of a material specification beyond SAE 1045. Of course, much of this information could be conveyed to the purchaser in a phone call before making the formal quotation. The more detail that is required to fill the order, the more complex the RFP and the PO become and the need for a material specification arises. Sometimes the purchaser will describe the intended application of the material, and this may alert the observant supplier to ask further questions, such as in the above example, whether or not the decarburized surface of the hot rolled bar is to be removed for a component that is to be subjected to fatigue loading in service. Information on the application of a forging is sometimes self evident in as much as it is obvious that a diesel engine crankshaft is expected to operate in a diesel engine, and the forging supplier should be aware—for his own protection—of the various material related factors that will affect crankshaft performance. Often there are few clues to the intended end use of a forging, and the forging manufacturer must simply follow the purchase order and specification requirements.

At one time many large companies wrote their own specifications and these were tailored to suit precisely their own operational needs. This often required that personnel were wholly dedicated to this not inconsiderable task, and once written these specifications required periodic revision to meet the changing needs of the company and the developments in the materials supply industries. With ever tightening fiscal restraints the ability to write and maintain inhouse material specifications has declined significantly in many cases.

There are some trade organizations that still write and maintain standards for their industries. Often these describe dimensional aspects of the products that their members make, an example being the MSS standards [1]. What then are the alternatives? Fortunately in the United States the national consensus standards writing bodies work diligently to write and maintain the backbone of the material specifications, test methods, and recommended practices that are used both in North America and abroad. A study of the steel forging standards published by ASTM is included in this volume, but it is worth emphasizing here that both the purchaser and the supplier should take the time and trouble to understand what is being bought and what is being sold from the perspectives of both parties. It should be realized that if there is a conflict between the requirements of the purchase order and the specification, then this should be resolved before melting steel or making parts. It is not always possible to say that the purchase order requirements take precedence, particularly if the specifications of a legally required code or practice are involved. For example, if the order is for the purchase of forgings for use in a pressure vessel that is to be covered under the rules of the ASME Boiler and Pressure Vessel Code, then the forgings must comply with a chosen material specification that is permitted in Section II of that code. Failure to do this can lead to rejection of the material or at best enduring the delays and uncertainties of trying to get the material accepted under the special rules of a Code Case. It, therefore, behooves the manufacturer (since he is the materials "expert") as well as the purchaser to make certain that the product meets all of the requirements of the material specification and construction code, as well as the purchase order, since in the case of a dispute the forging supplier may not be able to shelter totally behind the excuse of simply following the purchase order requirements. A corollary of this is that both the purchaser and the supplier should take an active interest in the development and maintenance of the national consensus standards.

Remembering that additional work on the forging may be done by the purchaser, or looking forward to experience when the part goes into service, there may be a need for more explicit details of the forging manufacturing history such as the full nondestructive examination reports, not simply that the forging met the minimum specification requirements. Admittedly, this involves some work on the supplier's part, although this is reduced if the request is known ahead of time, but the data can be invaluable in assessing later developments, be they failure analysis, remaining life assessment, or repair proposals.

The use of consensus standards minimizes the need for specific purchase order instructions. The Purchasing Requirements section in ASTM steel specifications helps in listing items that should be a part of the purchase order, and directs attention to the Supplementary Requirements section for specific items that may be relevant to the use of the forgings.

An admonition that was made during the specification reviews needs to be repeated here, and that is that attention must be paid to the scope clause of the chosen specification, to assure that the required forging application is covered. Failure to do this can mean that necessary quality assurance provisions for the application may not be met. This is particularly important for the end users of the finished equipment. It is not enough to know that some consensus specifications are included in the description.

A major aim of this review of the forging process is to assist the purchasing agent or manager to understand better the product relative to sending out an inquiry or placing a purchase order. It is hoped that the specification review will facilitate matching the need for a particular forging with the appropriate product specification relative to the application. To repeat, the purchasing agent is often the only direct link between the forging supplier and the engineer who needs the forging, and it should not be assumed in every case that the needs are fully understood in the request given to the purchasing department.

Reference

[1] SP 44 Standards for Steel Pipe Line Flanges, Manufacturer's Standardization Society of the Valve and Fittings Industry, 127 Park Street, NE, Vienna, VA.

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Forging Failure Analysis

Process Related

AN UNDETECTED, OR IGNORED, INGOT RELATED defect can be expected to show up as a forging defect, and may not be revealed until late in the production process for the component. Although some ingot internal problems, such as fully enclosed solidification voids, can be healed during forging, others such as surface cracks, pouring laps, and gross piping will give rise to defective forgings. This subject was discussed in Chapters 4 and 13, but it should be noted that it is not always apparent that problems encountered in a forging were the direct result of a condition in the ingot. As an example, during magnetic particle examination of cylindrical open die forgings in a modified SAE 4330 alloy steel, several transverse indications were detected. These were about 0.75 in. (18 mm) in length, and when probed, persisted to a depth of about 0.5 in. (12 mm). At the time they were detected about 1 in. (25 mm) of stock had been removed from the original forging surface, but later tests on other forgings showed that they actually began closer to the original forged surface. Etching of the indications in situ revealed that a decarburized envelope surrounded them, suggesting that they were present during heating for forging. Curiously, it was noted during the probing operations that the length of the indications essentially did not change until they were removed. All of this directed attention to the ingots that were from a big end down fluted forging ingot mold with a top diameter of 30 in. (750 mm). Since ingot porosity was suspected, cross sections from an ingot were hot acid etched. Those sections from the upper part of the ingot showed radially disposed, cylindrical near surface pores about the same length as the indications in the forgings, while those from lower in the ingot were pore free. The origin of the magnetic particle indications was now clear. Near surface, cylindrically shaped gas pores had been formed by reaction between carbon and oxygen in the steel during the initial solidification after the manner of a rimming steel. The ferrostatic head pressure in the mold had suppressed the pore formation lower in the ingot, and during heating for forging the proximity to the surface had permitted sufficient oxidation of the internal pore surface to impede the forge welding of the pores. The fix was to correct both deoxidation and vacuum degassing procedures during steel making. If surface NDE had not been a requirement, these defects would not have been discovered before delivery.

An important, if fortunately very infrequent, occurrence is the use of the wrong material for the forging. This can occur because of stock inventory problems, perhaps in marking or handling—one piece of scaled forging billet, of a given size, looks much like another, or simply by removing the wrong ingot from the forge heating furnace. In a busy forge shop on a given day there may be ingots of different steel grades from the same ingot mold being heated in the same batch furnace, and a scheme such as a closely followed chart is used to locate each ingot in the furnace. This is the responsibility of the furnace operator, often called the Heater. The problem here may not reveal itself until the mechanical testing stage is reached, when abnormal hardness, tensile or impact properties are obtained. A product analysis of course reveals the cause, but the next problem is to find the other forging made from incorrect material, and this may not always be so easy! Alertness is required on the part of those involved in machining, mechanical testing, and NDE examinations for situations that are noticeably abnormal, even if the required specification values are met, since the incorrect chemical composition may adversely affect subsequent welding operations or service conditions. This could be termed inadvertent grade substitution. Unfortunately, the intentional use of the wrong material has occurred often enough to warrant the insertion of grade substitution language in the steel specifications.

Forging

Apart from making the steel more difficult to work, low interior temperatures can lead to significant internal forging bursts. Although these may be revealed during machining or by NDE methods, again to the detriment of costs and schedule, examples have been seen of service failures attributable to such internal defects. Internal bursts generally exhibit a woody fracture appearance, and in some observed cases have been the origin for fatigue cracks spreading from inside to the outer surfaces. In one example, Fig. 21.1, a pinion forging with integral bearings was removed from an excavator after an inspection showed oil seeping from what appeared to be cracks on the end faces. Examination revealed an oval shaped internal burst lying along the axis of the pinion with fatigue cracks that had propagated outwards from the periphery of the crack. At that time the pinion had not quite separated into halves. In this example an alert machinist could have detected the problem long before the pinion was put in service.

Carbon segregation can lead to problems in forgings made from the larger ingots, notably those weighing in excess of 15 tons (14 t). The carbon content can vary significantly from top to bottom of the ingot [1], leading to differences in mechanical properties after heat treatment. This effect has been noticed in very large ship propulsion shaft forgings made from ingots weighing more than 30 tons (27 t), to the extent that the tempering temperature had to be adjusted along the length of the shaft.

Hydrogen Damage

The adverse effects of hydrogen are well known in the welding of steels, where the term "Fish Eyes" is often used. These

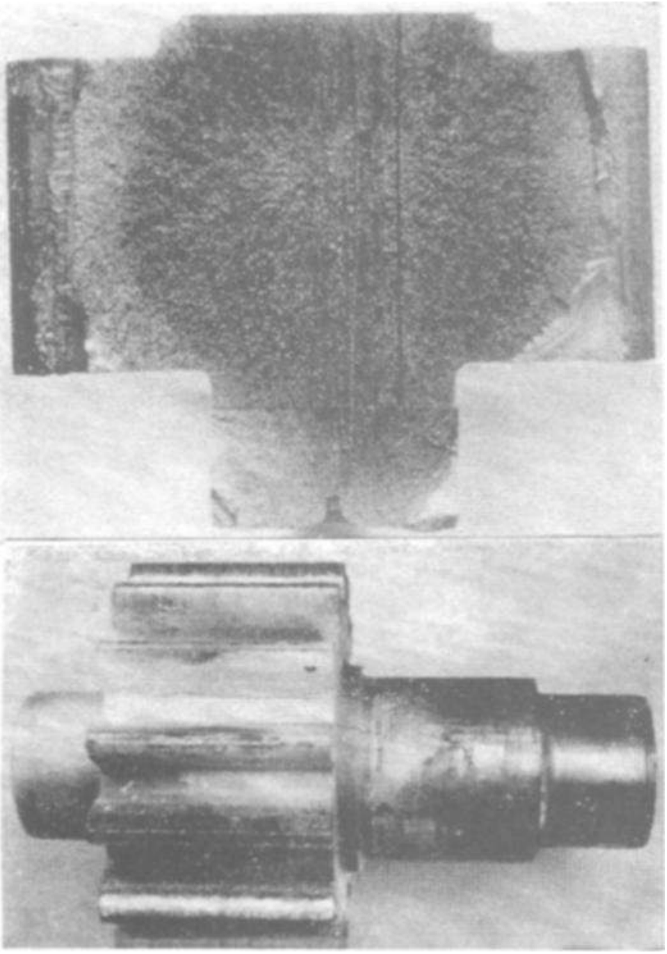

Fig. 21.1—An excavator pinion about 18 in. (450 mm) in diameter that was removed from service because of visible longitudinal cracking. The cause was an original internal forging burst that propagated during heat treatment and then propagated further outwards by fatigue in service. The cracking could have been detected during machining, as well as by surface NDE.

effects can be seen on the fracture surfaces of tension test specimens, Fig. 10.1, and often in failed bend tests. They are characterized by shiny light colored elliptical fracture surfaces, each with a tiny dark spot near the center, hence the term "eye." Similar effects are sometimes found during the tension testing of forgings, and are accompanied by a drastic loss of ductility, both in elongation and reduction of area. Careful inspection of the eye, and there may be more than one, will reveal a small inclusion in the fish eye, and examination in a scanning electron microscope (SEM) will show an intergranular fracture, characteristic of the presence of hydrogen. Baking the tension test specimen at about 500°F (260°C) for an hour or two will restore ductility, but if this is to be used, then the forging should be baked as well, with the hold time adjusted for the section thickness. Hold times of the order of 10 h/in. have been used for this purpose.

Fatigue

In dealing with defects and production problems in forgings, the reader is apt to be left with the impression that all service failures and difficulties can be laid at the forging's door. Nothing can be further from the truth. In practice, manufacturing defects in forgings are generally apparent before the forging is to be shipped, and thus become an "error and defect" cost, together perhaps with a schedule delay. Undetected defects that surface in service are relatively rare. What then is the major reason for in-service failure? The short answer to this is fatigue, and although the causes of fatigue failure have been known, for about a century, in many cases they are still disregarded. The repeated application of a load to a component can lead to failure at stresses, much lower than the tensile or yield stress of the material, if the number of load cycles is high enough. This is known as fatigue. The classic example is for a rotating shaft mounted on bearings. The shaft will have a tendency to sag between the bearings, inducing compressive surface loads at the top and tensile loads at the bottom. As the shaft rotates an alternating tension/compression load cycle is set up and if these stresses are high enough, failure can be anticipated after many load reversals. As the loads are reduced the number of cycles to failure increases until a steady state condition exists when failures do not occur; this is known as the endurance limit for the material, and as a rule of thumb is approximately half of the tensile strength. However, it should be noted that surface condition is of paramount importance when considering fatigue. Surface finish, and even the methods used to achieve this finish, are critical aspects in considering the fatigue life of a component. Geometric features must be considered also. Simple features, such as a change in cross section or a keyway, have an enormous influence on the life of a component operating under alternating stresses. It is essential to minimize stress concentration points, so that at a change in cross section, for example, a generous smooth radius is necessary. Similarly for a keyway, no sharp corners should be present, and the fewer and shallower the machining marks are on the surface, the better it is for extended life. Some of these requirements cut across low cost machining and assembly practices. For example in a keyway, machining sharp corners comes naturally to the process and simplifies making the key for the desired snug tight fit. Introducing the necessary radii into the keyway for good fatigue life increases machining and assembly costs. The author's first job was in an aero engine factory that made large sleeve valve radial piston engines. Suspended from the ceiling joists all through the vast machine shop was the exhortation No Sharp Corners! It should be remembered that although surface condition is of paramount importance in considering fatigue strength, failures can originate at subsurface locations in the presence of significant stress risers, such as the examples shown in Figs. 21.1 and 21.2.

While in certain industries the importance of surface finish and component design because of fatigue was well known, in others the lessons were less so. An example was the case of the Comet, an early pressurized jet powered airliner. The airframe designers were apparently less familiar with the requirements for fatigue prevention in a pressure vessel (the fuselage) than their colleagues in the same company that produced the jet engines, with the result that fatigue cracks originating at the window openings caused catastrophic rupture of the fuselage in flight. A similar situation existed in the ship building industry when welding began to replace riveting for hull construction. In riveted construction it is difficult for a crack to propagate through the joint into the next plate; this difficulty disappears with welded con-

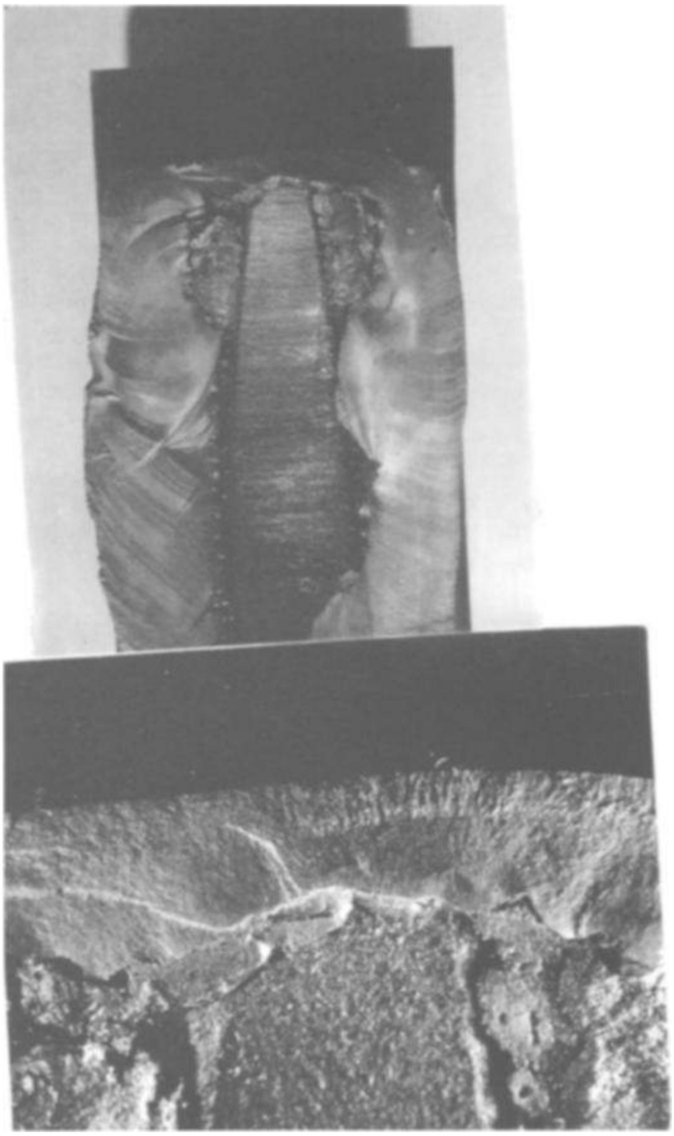

Fig. 21.2—Failed crankshaft counterweight weld from a CGF crankshaft. Although the fillet weld had ample throat thickness along the sides of the counterweight, the welds were inadequate at the ends of the counterweight post where centrifugal forces in service are high. Fatigue cracking started at the weld root at the ends of the post and propagated through most of the fillet weld section before the counterweight flew off.

struction and construction features such as loading hatch corners assume critical importance. Here a fatigue crack can develop at a stress concentration and result in a catastrophic brittle failure. Although the numerous Liberty ship brittle failures during World War II were attributed to brittle failure due to the poor notch toughness of the hull steels, it is likely that attention to good fatigue resisting design and construction features such as the absence of areas of high stress concentration could have prevented many of the failures.

Some components are more complex than others with respect to fatigue loading. For example, an internal combustion engine crankshaft presents special situations with numerous highly stressed areas. During the compression and firing strokes high bending stresses are imposed on the crankpin and main bearing radii. In addition, both torsional and bending stresses are experienced at the lubrication holes in the bearing journals. The radii at the oil holes and between the journals and the crankshaft webs must be large and smooth with no machining ridges. Providing residual compressive stresses at these surfaces is beneficial to crankshaft life. These compressive stresses can be obtained by cold working the surfaces, for example, by rolling or shot peening techniques, or surface hardening by nitriding or induction hardening. A machine for induction hardening crankshafts is shown in Fig. 12.4. However this is done, the final surface finish is a paramount factor. Since surface grinding is often used to obtain the final dimensions and surface finish, care must be taken to avoid the tiny surface grinding cracks that will readily act as origin points for a fatigue crack. Cracking caused during grinding is a subject in itself and was discussed in Chapter 8, but generally is attributed to the grinding media becoming clogged and burnishing the surface rather than cutting it. The timely dressing of the grinding wheel is very important, but even the diamond quality used for this purpose has been found to be a factor. In the author's experience, even the use of worn silicon carbide polishing cloth with power tools on a hardened steel surface can cause shallow cracking.

Another factor that can promote fatigue failure is surface decarburization. This can occur when insufficient stock is removed from the surface following heat treatment. The decarburized skin has a lower strength than the underlying material, and hence a lower fatigue strength. Although not considered to be forgings, coil and leaf springs can be prone to this problem, together with any seams or rokes remaining from the original rolling operation that can act as stress risers for fatigue failures.

It is worth noting here that some fatigue failures result from repair procedures that weaken the surface when restoring a dimensional problem. Frequently, such repairs involve welding and sometimes peening. Reports have appeared in the literature, and the author has personally investigated similar instances, where a mis-machined keyway or shaft journal has been rebuilt by welding and remachined to size. Sometimes the weldments had cracked, perhaps due to lack of preheat, or some other weld defect had left a surface stress concentration. In others, the fatigue strength of the weld deposit was inadequate for the application. A popular design of diesel electric locomotive crankshaft was made by two crankshaft manufacturers. The shafts produced by one of them experienced several counterweight weld failures in which a counterweight would be thrown off the crankshaft, damaging both the shaft and the crankcase. Examination of a failed counterweight attachment weld, Fig. 21.2, clearly showed that the weld had failed by fatigue originating at the partial penetration weld root at the ends of the counterweight post. There was insufficient depth of weld at these locations. Counterweight welds from the second manufacturer had been made using better weld preparations and gave no service problems.

In some applications for ship shafting a copper alloy bearing surface is required. If the shaft is flanged at both ends, a split sleeve that is joined in situ on the shaft can be used, using the weld shrinkage to hold the sleeve in position on the shaft. However, precautions must be taken to avoid welding onto the shaft surface, because of the risk of intergranular copper penetration of the shaft surface. This risk of intergranular copper alloy penetration in steel can be much reduced if the forging is stress relieved before welding.

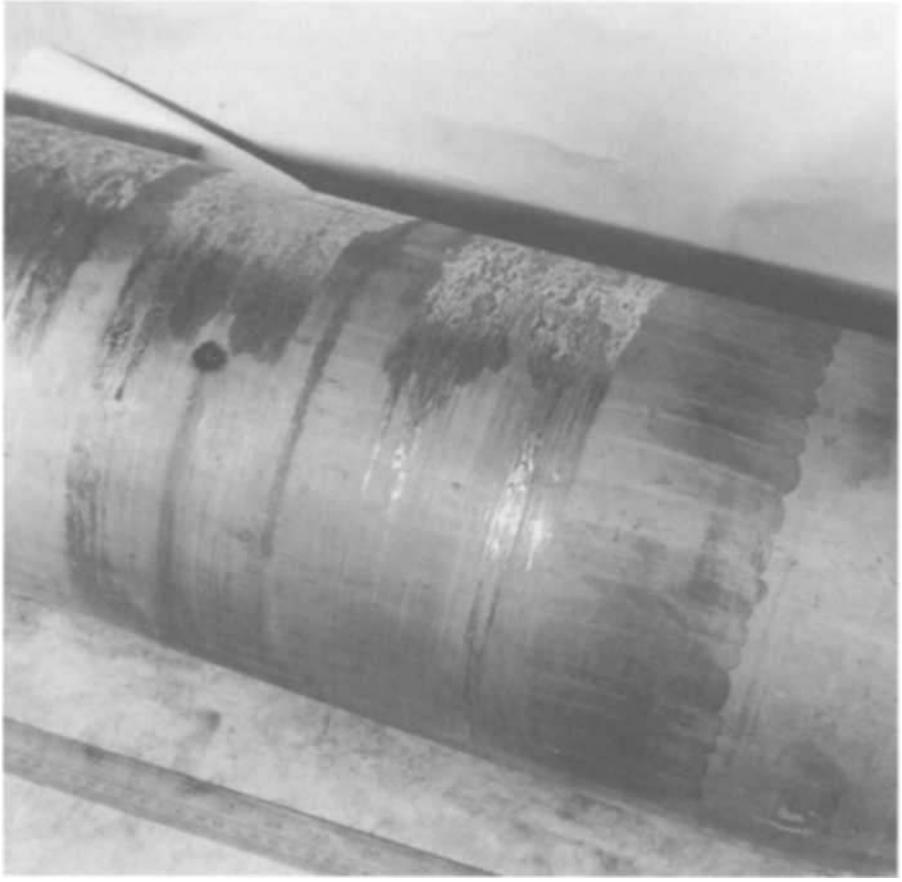

Fig. 21.3—Failure of a crane sheave shaft forging shortly after weld restoration of the bearing surface. The weld beads of the repair can be seen as well as the overlay of bronze from the sheave bearings. Bearing seizure appeared to be through lack of lubrication, and molten bronze had penetrated the shaft surface. Brittle fracture of the shaft started at the bronze penetration areas. The shaft microstructure was coarse apparently through lack of heat treatment leading to low toughness.

Failures due to copper alloy surface penetration of steel have been observed in crankshafts where a bearing seizure resulted in deposition of the copper alloy on a journal surface. The journal had been cleaned of adhering metal particles from the damaged bearing, fitted with new bearings, and restored to service, to be followed soon after by fracture of the journal by fatigue. In a similar incident, following a bronze bearing seizure on a weld repaired sheave shaft from a crane, replacement of the bronze bearing was followed by a brittle fracture of the sheave shaft, Fig. 21.3. The fracture

Fig. 21.4—Failed cement kiln shaft forging. Failure was by fatigue originating at bronze grain boundary penetration stemming from an earlier bearing seizure. The shaft surface had been cleaned but particles of bronze could still be seen. Notice the alignment of the fracture path with the circumferential scores that were sites of bronze penetration.

origin was a small fatigue crack originating at a grain boundary bronze penetration site. A fractured shaft from a cement works is shown in Fig. 21.4. The fatigue fracture in this case again started at a bronze penetration site caused by a bearing seizure.

Corrosion Fatigue typically occurs in components that are subjected to alternating stresses whilst in corrosive environments, such as a carbon or alloy steel part (e.g., a rotating shaft that is operating in an aqueous environment). The fatigue strength is significantly degraded in such circumstances and measures must be taken to protect the stressed surfaces. A common incidence of corrosion fatigue is found in steam boilers in locations subject to repeated heating and cooling. Superheater headers are an example. In order to control the superheated steam temperature, water sprays are often used to reduce the steam temperature. A baffle is usually placed to prevent water droplets from hitting the header ID surface, but if this should happen, the repeated localized spot heating and cooling of the header wall can cause sharp transgranular cracks that will rapidly penetrate it. This problem should not be confused with stress corrosion in which, for a given material, specific corrosive agents in conjunction with applied or residual stresses can cause extensive cracking. For many, but not all materials, this cracking is intergranular. The problem is known by various names; for example, *Season Cracking* in brass is associated with ammonia together with high residual stresses. In the carbon steels, *Caustic Cracking* is associated with the concentration of sodium hydroxide from the boiler feed water at areas of high residual stress, such as at rivet holes in riveted boiler shells. Similar cracking has been found near welded seams that were not stress relieved.

The correction of these problems can involve stress relief of the component, effective in the case of brasses when the environment cannot be changed, or by removal of the corrosive agent, as is the case for boiler feedwater treatment for boilers.

Liquid metal embrittlement or attack is often another form of stress corrosion. Copper alloy weld overlays on carbon or alloy steels have been known to result in grain boundary penetration of the base material. Stress relief of the part before overlaying has been found to be helpful in such cases. However, it is not always easy to identify the cause of the attack, particularly if the manufacturing and use histories are not known; and all these problems are generic and not associated simply with forgings.

Reference

[1] Kim, J., Pyo, M., Chang, Y., and Chang, H., "The Effect of Alloying Elements Steelmaking Processes on the "A" Segregation Occurrence in Large Ingots," *Steel Forgings, ASTM STP 903*, Nisbett and Melilli, Eds., 1984, pp. 45-56.

22

Postscript

THE FORGING OF STEEL HAS PROGRESSED FAR from its initial use of agglomerating and consolidating small batches of iron and steel before forming them into useful products, to the current high integrity forged components that are used, and taken for granted in everyday life. The provision of vital utilities such as electricity, gas, and water, as well as transport by land, sea, and air all depend on the integrity and availability of steel forgings.

Understanding of the contents of the scope clause that is a part of each of ASTM International's specifications is essential for the successful application of the standards. If a forging product specification is to be used for an application that is not mentioned in the scope, the requirements of the specification should be considered relative to the expected performance of the forging rather than the first cost. For example, Specification A 723/A 723M, Alloy Steel Forgings for High-Strength Pressure Component Application, has been used to advantage in the manufacture of structural anchoring components for an offshore oil platform because besides offering the necessary mechanical properties it includes extensive testing requirements to give the needed quality assurance.

This work describes not only the features that go into making forgings, but also the tools in the form of consensus standards that enable the manufacturer and user to define the required product, and make an intelligent choice of the manufacturing controls that are appropriate for the intended use. It is hoped that these aims have been achieved.

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