CHAPTER 39

Manufacture of Heavy Press Forgings

This chapter will be confined to discussion of the production of steel forgings of large size in hydraulic presses utilizing open dies, and will be based generally on the practices employed at one plant of United States Steel Corporation. Capacities of the hydraulic forging presses at this plant are 88,964, 35,586 and 17,783 kilonewtons (10,000, 4,000 and 2,000 net tons force). Auxiliary equipment includes furnaces of ample capacity for heating and reheating ingots and forgings, complete heat-treating facilities, and machine tools designed to handle the massive forgings that are produced.

The principle of operation of the hydraulic press was outlined in Chapter 22, along with a comparison of forging with other methods for the hot-working of steel. Although steel can be hot-worked in various ways, perhaps no other method of hot-working can surpass the forging process for producing the best combination of properties.

Open-die forging may be defined as the hot-working of steel between flat or contoured dies. This hot work produces the following advantageous effects: refinement of the relatively coarse crystal structure inherent in the as-cast ingot; performance of sufficient work on the ingot to obtain the desired mechanical and metallurgical properties; and production of a sound, homogeneous mass of steel of the desired size and shape. Typical large forgings produced by the methods to be described are used for generator shafts, steam-turbine rotors, hydroelectric shafts, marine propulsion shafting, ring- and disc-type nuclear components, work rolls, sleeves, die blocks, and miscellaneous mill-equipment parts. Forged billets, blooms and slabs for further working in customers' plants are also produced.

HEATING FOR FORGING

Rate of Heating—At this plant, the majority of large forgings are produced from ingots from 1320 to 3405 mm (52 to 134 inches) in diameter and weighing up to 366,500 kilograms (808,000 pounds). Such large masses of steel require careful control of heating practices that must be varied according to the chemical composition, size, and prior thermal history of the ingots. These same factors govern the several reheating operations usually involved in the production of forgings of large section. The general aims in the control of heating operations are the attainment of a uniform temperature throughout the ingot or reheated forging, and establishment of heating rates that will achieve proper degree and uniformity of temperature in the shortest practical time. Practical considerations related to time and rate of heating are the minimizing of the amount of scaling and decarburization of the steel surfaces.

Furnaces of the direct-bred car-bottom type (Figure 39–1) are popular for heating large ingots and forgings. Any furnace employed for this work should be equipped with suitable instrumentation for the accurate measurement, control, and recording of temperature.

Only general rules can be prescribed for heating large sections. Large ingots or forgings should be heated slowly and uniformly. The rate of heating fairly well establishes the length of time necessary for the steel to attain forging temperature throughout its mass, and a rate should be selected that avoids excessive temperature differentials between the inside and outside of the mass. The temperature of the interior lags behind that of the exterior during a large part of the heating cycle, and a period of time near the end of the cycle must elapse after the exterior has attained forging temperature for sufficient heat to be conducted into the interior to raise it to the proper temperature. The slower the heating rate, the shorter will be the time for such temperature equalization to take place. Step heating may be employed; that is, the steel may be held at one or more temperature levels below forging temperature and allowed to equalize before proceeding to a higher temperature level. It has been found that after its temperature has been equalized at a point slightly above the upper critical temperature (about 800°C or 1473°F), steel can be heated at a rate of 22° to 33°C (40° to 50°F) per hour until forging temperature is attained. This cycle results in heating times corresponding to approximately ¼ to 1 hour per 25 mm (1 inch) of diameter or thickness of the ingot or forging. In general, carbon steels containing over 0.50 per cent carbon and alloy steels require slower rates of heating than carbon steels of lower than 0.50 per cent carbon content.

Forging Temperature—Forging temperature is selected to provide the best condition for hot-working a given steel. Although the final properties of a finished forging are established largely by heat treatments applied subsequent to hot-working, the temperature at which hot-working is completed influences, to varying
degrees depending on grade, what heat treatments are necessary as well as the final mechanical properties of the steel. In general, lower finishing temperatures result in a finer-grained microstructure when forging is completed. The finer-grained structures respond better to heat treatment than do coarser-grained structures. However, the finishing temperature must be kept high enough to prevent the occurrence of forging bursts (internal ruptures) that may result from severe stresses induced by working large masses of steel at too low a temperature.

Soaking times at the forging temperature are also important, particularly in the hot working of the austenitic grades of steel. The times should be sufficiently long to accomplish the achievement of uniform temperature throughout the steel, but not so long as to promote excessive grain growth of the austenite. Since the austenitic stainless steels do not undergo a phase transformation during heat treatment, the final grain size of a forging is determined by the hot-working process. Poor control of forging temperatures or soaking times can result in an extremely coarse grain size in a stainless-steel forging, which then cannot be evaluated by ultrasonic inspection due to the tendency for the coarse grain structure to attenuate or scatter the sound wave.

Caution must be exercised to avoid overheating and burning of the steel. The safe upper limit of the hot-working range is a suitable temperature interval below the melting point of the lowest-melting constituent of a steel. Burning consists of heating a steel to a high temperature in an oxidizing atmosphere so that actual fusion and oxidation occur at the austenite grain boundaries, causing hot shortness that results in badly torn surfaces and internal ruptures during hot working. Burned steel cannot be salvaged. Overheating has less obvious effects, caused by heating to a high temperature but not sufficiently high as to cause burning. The effects of slight overheating can be removed by subsequent hot working, but more severe overheating can cause low ductility and low toughness in forgings tested after final heat treatment.

**HANDLING EQUIPMENT**

Special equipment is required for handling the heavy masses of steel represented by forging ingots and the forgings themselves.

Electric overhead traveling cranes with special lifting devices are employed in charging ingots and forgings onto and from the hearths of car-bottom heating furnaces, and for transporting them to and from the forging presses (Figure 39—1).

An electric crane at the forging press carries a turning gear suspended from the main hoist. The turning gear consists of a frame carrying a drum that can be rotated by an electric motor through gearing. An endless chain called a sling, constructed of flat links and
pints, passes over the drum and moves with it (Figure 39—2).

A device called a porter bar has a hollow end shaped to fit the sinkhead of the ingot being forged. The load represented by the ingot and porter bar is balanced by placing the sling at the center of gravity of the combined load (Figure 39—2); the sling has to be moved from time to time to preserve balance as the dimensions of the forging are changed.

Faster and more accurate handling of the hot steel during forging is accomplished by the use of machines called manipulators. These machines are equipped with powerful tongs at the end of a horizontal arm that can be moved from side to side, raised or lowered, and rotated about its longitudinal axis. The manipulator shown in Figure 39—3 operates on tracks in the floor in front of a 88 964 kilonewton (10 000-net-ton force) hydraulic press, and has a capacity for handling pieces weighing up to 68 metric tons (75 net tons). Smaller manipulators are designed to operate on wheels that have resilient or solid tires.

OPEN DIES FOR FORGING

The dies used in open-die forging are of three basic types, shown schematically in Figure 39—4. They are known as flat dies, V dies, and swage dies. For hollow forgings or ring forgings, a mandrel or expanding bar is inserted in a hole in the piece to be forged, and forging is carried out by utilizing the mandrel or bar as the bottom die.

PRINCIPAL FORGING OPERATIONS

Superior quality, toughness and strength characteristics have gained for forgings their reputation for dependability under the most severe service conditions. The consecutive operations employed in producing heavy press forgings by open-die forging are carefully planned and executed in proper order so as to arrive at the final contour (in which the sections may vary greatly) while at the same time achieving the proper degree of grain refinement and internal soundness.

Initial working of an ingot is usually referred to as cooging (Figure 39—5), and removes the flutes, ripples or corrugations that were formed on the ingot as it solidified in a contoured mold and which are intended to prevent cracking of the ingot surface during solidification and cooling. Light drafts (small reductions) are taken all over the ingot until the surface irregularities
Fig. 39—3. Heavy duty manipulator holding an ingot in position while a 88 964 kilonewton (10 000-net-ton force) press squeezes the hot steel into the rough shape of the finished product.

![Diagram of dies](image)

**Fig. 39—4.** Basic shapes of dies for open-die forging.
are smoothed. Heavier drafts are then taken and working continues, usually to convert the cross-section of an originally round ingot to an octagon shape, then to a square, back to an octagon, and so on. This straight-down or setting-down type of forging (Figure 39—5), also called drawing out and forging solid, is used on products such as blooms, rounds, and shafting having constant or variable section size, in which the work flows in a longitudinal direction. For variable section sizes or step-downs, marking knives or veering tools are used to mark off the necessary volume of metal for any particular section (as shown later in Figure 39—11).

Upsetting (sometimes called pancaking) is employed to alter the geometry of a piece. For example, forging pressure applied to the ends of a cylindrical piece will shorten its axis while increasing its diameter. Upsetting also produces a benefit that results from circumferential flow that induces the best condition for parts subjected to either tangential or radial stresses, or both. Upsetting is used to produce disc-type forgings and is sometimes employed as an intermediate operation in the production of steam-turbine rotors. In this instance, the ingot is forged to a bloom of predetermined size, usually octagonal in shape, and a slug of sufficient length is sheared. The slug is upended and forged to reduce its length, with the percentage of upsetting being based on the grade and size. Further forging consists of reworking along the length, marking, and contouring. Benefits derived from this sequence of operations include working in all directions to enhance soundness and reduce the directionality of properties. In upsetting, it is necessary to keep the length of the slug within certain limits (usually not more than 2½ times the octagon size) to prevent kinking or bending during upsetting. In some types of upsetting operations, hollow, cylindrical die-like tools called bolsters may be employed to retain part of the slug and prevent change in its dimensions while the upsetting force is applied to deform the rest of the slug. A simple application of a bolster is shown schematically in Figure 39—7.

Piercing and punching are performed by forcing a solid punch into hot steel to form a cavity. Piercing is employed to make a blind cavity by displacement without removal of metal. Punching produces a hole that extends through the entire section and both displaces and removes metal in the form of a slug. Sometimes a

**Fig. 39—5.** Large corrugated ingot in the process of being “cogged” or reduced to an octagonal shape during the first stage of forging.

FIG. 39—7. Schematic representation of the use of a bolster to maintain a previously forged tonghold on a piece during up-setting.
hollow punch is used to remove some of the central metal as a core; this operation is generally termed hot trepanning or hot trephining.

Expanding is a special process for increasing the diameter of hollow forgings. It can be used for finishing hollow forgings or to increase the size of the hole prior to finish forging on a mandrel. It is also employed in the forging of rings. For expanding a forging of considerable length, a top tool with a narrow face parallel to the expanding bar is used (Figure 39—8), to keep the length-wise elongation of the piece to a minimum while reducing the thickness. As shown in Figure 39—8, the bottom die is replaced by an expanding bar or mandrel that passes through the opening in the forging and rests on supports beyond the forging. When pressure is applied, the thickness of the material between the top tool and the bar is reduced, displacement of the metal resulting in an increase in the circumference of the forging. By successive incremental movement of the work piece followed by pressing, the wall thickness can be reduced uniformly while attaining the desired inside and outside diameters. Uniformity of temperature throughout the piece is important for successful control of expanding, and a bar of sufficient strength to withstand the bending moment is essential. Figure 39—9 illustrates the forging of a large ring on an expanding bar.

The process of hollow forging on a mandrel differs somewhat from the expanding process, in that the mandrel establishes the inside diameter as the piece is forged with pressure from opposed top and bottom tools. As shown in Figure 39—10, the hollow work piece is fitted to a mandrel of the desired size that is supported on both ends to position the work between

Fig. 39—9. Forging a large steel ring in a hydraulic press, using an expanding bar.
the top and bottom dies. Narrow-faced tools are used in this type of work to cause the metal to flow lengthwise of the piece. The mandrel is usually tapered slightly to facilitate its removal from the finished forging.

Closing in is an operation on a hollow forging, using flat, tapered, curved, or formed dies, to partially close the end, or reduce some other portion of a forging; as, for example, in forming the hemispherical ends of a boiler drum. One or more local reheats of the part of the forging being worked are usually involved.

Slabbing consists of forging an ingot to a large, heavy slab or plate section that is beyond the capabilities of rolling facilities.

EXAMPLES OF FORGING PROCEDURE

Figures 39-8, 39-9 and 39-10 have shown the principles employed in making hollow forgings such as cylinders and rings. These expanding and elongating principles are used singly or in combination to forge boiler drums, chemical reactors, pressure vessels, roll sleeves and many other products.

Figure 39—11 shows the steps in producing a sleeve for a cold-reduction-mill back-up roll. Such sleeves generally are made from a high-carbon (0.65 to 0.75 per cent) nickel-chromium-molybdenum-vanadium steel. This particular sleeve has a 1084 mm (42% inch) outside diameter, a 711 mm (28-inch) inside diameter, and a 1089 mm (42% inch) body length. Three sleeves of this size are produced from a 1219 mm (48-inch) diameter ingot weighing 33,000 kilograms (72,800 pounds). The round, corrugated ingot is first forged to a 1118 mm (44-inch) octagon, then sheared into three pieces, each 1067 mm (42 inches) in length. The pieces are reheated and each is upset forged to 974 mm (36 inches) in length, after which a 410 mm (16% inch) diameter hole is punched through the longitudinal axis of each. After reheating, each piece is forged on a 406 mm (16-inch) diameter expanding bar to increase the hole to 558 mm (20-inch) diameter. Each expanded piece is again reheated and forged on a 495 mm (19% inch) diameter bar to a 997 mm (39% inch) octagon and the hole is enlarged to 533 mm (21 inches). Another reheating is followed by forging the ends of each piece to a level contour. After a final reheating, the sleeves are each forged on a 483 mm (19-inch) diameter bar to 660 mm (26 inches) in inside diameter, 1133 mm (44% inches) in outside diameter, and approximately 1346 mm (53 inches) in length. After this final forging operation, the sleeves are slowly cooled, then heat treated to secure the proper microstructure for subsequent hardening by water quenching and tempering, following rough machining.

A Ni-Mo-V generator-rotor shaft with a forge weight
of 68 to 73 metric tons (75 to 80 net tons) and a rough-machined weight of 50 to 54 metric tons (55 to 60 net tons) would be forged in three heats from a 134 metric ton (170 net ton), 2413 mm (95-inch) diameter ingot. On the first forge heat, the corrugated ingot body is forged to approximately a 1397 mm (55-inch) octagon, the sinkhead is sheared off, and a chuckhold forged on the top end. On the second heat, the ingot is further reduced to approximately an 1194 mm (47-inch) octagon, marked and "veded" to define the body and journal steps, and at this stage the bottom discard is sheared off. On the third and final heat, the various steps from body to journals are forged to size, a final forge pass made on the body, and the top chuckhold sheared off. The appropriate slow cooling, heat treating, and machining operations are carried out before the shaft is shipped.

COOLING AFTER FORGING

It is important that large forgings be cooled after hot-working is finished in a manner that will prevent the formation of thermal bursts or ruptures caused by internal stresses related to differences in rate of cooling of different parts of the forging, or flakes that are attributed to gases (particularly hydrogen) absorbed by the liquid metal during steelmaking. As described in Chapter 19, vacuum stream degassing of molten steel to lower the hydrogen content to safe limits will effectively prevent formation of flakes, even in very large ingots, and consumable-electrode melting and vacuum melting (see Chapter 18) can achieve the same end in smaller ingots. However, prevention of damaging internal stresses can only be achieved through closely controlled cooling. For applications where minimum residual stresses are necessary, very slow cooling rates and long tempering times are advisable.

HEAT TREATMENT OF FORGINGS

Few heavy forgings are shipped without some form of heat treatment. Here, horizontal car-bottom furnaces and vertical pit-type furnaces are used, depending upon the shape and weight of the forgings undergoing heat treatment.

Typical heat-treating operations include:
1. Annealing (various cycles).
2. Normalizing (with optional accelerated air-cooling) and tempering.
3. Water or oil quenching followed by tempering, utilizing tanks for quenching.
4. Water-spray quenching, followed by tempering.
5. Stress relieving.
6. Various combinations of the above.

Car-Bottom Furnaces—The plant has thirteen car-bottom furnaces for the heat treatment of forgings. These are direct top-and-bottom fired, using natural gas as fuel, and have a maximum operating temperature of 1060°C (1940°F).

Vertical Furnaces—Seven vertical pit-type furnaces are available for heat treating large and lengthy shafting, steam-turbine rotors, generator shafts, and similar types of forgings.

The principal use of these furnaces is for grain-refinement treatments and stress relieving of rotors and shafts. A part of these furnaces is below ground level, as shown in Figures 39—12 and 39—13. All seven of the furnaces are charged from the top by an overhead crane. Work rests on a special hearth casting at the bottom of each furnace and is stabilized by pins inserted through sides of the furnace to contact the forging, except in one furnace that has a rotating hearth that revolves the charge about its longitudinal axis throughout the heating cycle. Natural-gas-fired burners fire tangentially into the heating chambers to prevent flames from impinging directly on the charges and to circulate the products of combustion in a manner that promotes temperature uniformity in the furnaces.

A typical heating cycle consists of a heat-up period at a controlled rate of temperature rise, a soak period, another heating at a controlled rate to a higher temperature, another soak period, and then a controlled cooling period. Because of the slow cooling rates involved, it is usually necessary to provide a small amount of heat to maintain the desired rate of cooling. When the natural cooling rate is slower than that desired, the gas is shut off and the proportioning controller operates the air valve only, thus increasing the cooling rate. A complete heat-treating cycle can last from one to eight days.

Quenching Facilities—Some forgings to be quenched in liquid media (water or oil) require a more rapid cooling rate than air-cooling in the furnaces can provide. For this purpose, a vertical quench chamber (Figure 39—14) is located near a battery of the pit-type furnaces. Forgings are positioned vertically and held securely in the base that can be rotated continuously during the quenching operation. A variety of cooling media can be employed, such as water spray, fog spray, a combination fog-and-air spray, or an air quench.

For liquid-media quenching, the plant has tanks of ample dimensions, equipped for forced circulation.

TESTING AND INSPECTION OF FORGINGS

The forgings produced are manufactured in accordance with various customer or industry standards which specify desired material characteristics and properties. In addition to the usual dimensional considerations, the specified requirements may be many or few; and may, for example, relate to chemical composition, mechanical properties, heat treatment and machined-surface finishes. Non-destructive tests, such as ultrasonic and/or magnetic-particle testing, may be specified to determine the presence of internal or surface discontinuities.

Mechanical-Property Tests—Various tests are employed to measure the mechanical properties of heat-treated forgings and include:
1. Tension tests
2. Impact tests (Charpy V-notch, drop weight)
3. Hardness tests (Brinell, Rockwell, Shore Scleroscope)
4. Bend tests
5. Corrosion bend tests
The above tests are discussed in more detail elsewhere in this book.

When tension, impact or bend tests are specified, provision must be made for testing at locations within
Fig. 39-12. Forging positioned over one of a battery of four pit-type heat-treating furnaces (see also Figure 39-13).
Fig. 39—13. General view of battery of pit-type furnaces (right) and vertical quench chamber (left) for the heat treatment of large forgings. Generator-shaft forging is shown rotating about its vertical axis within the quench chamber, the doors of which normally are closed during operation but which were left open for this photograph.
the forging which will not result in destruction of the forging, or from excess test-metal prolongations added to the forging configuration. Location and size of the added test-metal prolongations are determined by the orientation of the test-specimen axis. On most forgings, the tests are oriented parallel to the direction in which the forging is most drawn out or extended by forging, i.e., on shaft forgings, test specimens are parallel to the

Fig. 39—14. Generator-shaft forging being lowered onto holding fixture on rotating base of quench chamber. Structure at floor level in left foreground is an upending cradle that raises long forgings from a horizontal position to a vertical position to facilitate handling by crane. Sliding vertical doors close front of chamber during quenching.
axis of the forging; on disc-type or ring forgings, test specimens are oriented tangential to a circle drawn using the axis of the forging as a center. Steam-turbine and generator forgings which are subjected to high rotational stresses in service require adequate transverse properties and are tested in a direction perpendicular and radial to the forging axis. Typical test plans for various types of forgings are shown in Figure 39—15. Actual removal of test specimens from the forging can be accomplished in a number of ways, such as sawing and trepanning, or from blocks removed by an electrochemical milling machine.

Hardness tests are made in prepared areas of the forgings at locations required by the material specification. Sufficient metal is removed from the surface of the specific test site to eliminate decarburization and other surface irregularities.

Non-Destructive Testing—The internal and surface quality of forgings is verified by one or more of the following methods which are covered in more detail in other chapters.

1. Visual inspection
2. Ultrasonic inspection
3. Liquid-penetrant inspection

Surfaces of forgings are inspected for imperfections by visual means which may be supplemented with either liquid-penetrant or magnetic-particle test methods. Optical periscopes may also be employed to inspect inaccessible areas such as the bores of shaft-type forgings.

Internal quality of forgings is evaluated by ultrasonic methods using a longitudinal wave, and, when required, shear-wave techniques. The inspections are performed using 0.5, 1.0, 2.25 or 5.0 MHz transducers with the instrument calibrated to display a specific back-reflection response from the forging itself or from an artificial flaw (flat-bottom hole) placed in the forging or in a compatible external test block. Distance-amplitude corrections may also be employed to evaluate flaws at various positions within a long test distance. A typical distance-amplitude curve is shown in Figure 39—16.
Fig. 39—16. Flaw-size estimation using distance-amplitude correction. (Left) Distance-amplitude curve for 2.25-MHz 1-inch-diameter crystal in normalized low-carbon nickel-chromium-molybdenum steel; 100 per cent amplitude is equivalent to 17.81 mm² or 0.0275 in.² (4.76-mm or %1-in-diameter) reflecting area. (Right) Schematic sections of cylindrical sonic test blocks with different test-metal distance (TMD). Flat-bottom holes are 3.18 mm (1/8 in.) in diameter, 19.05 mm (¾-in.) deep, plugged at open end.