Open-Die Forging

Revised by the ASM Committee on Open-Die Forging
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OPEN-DIE FORGING, also referred to as hand, smith, hammer, and flat-die forging, can be distinguished from most other types of deformation processes in that it provides discontinuous material flow as opposed to continuous flow. Forgings are made by this process when:

- The forging is too large to be produced in closed dies
- The required mechanical properties of the worked metal that can be developed by open-die forging cannot be obtained by other deformation processes
- The quantity required is too small to justify the cost of closed dies
- The delivery date is too close to permit the fabrication of dies for closed-die forging

All forgeable metals can be forged in open dies.

Size and Weight

The size of a forging that can be produced in open dies is limited only by the capacity of the equipment available for heating, handling, and forging. Items such as marine propeller shafts, which may be several meters in diameter and as long as 23 m (75 ft), are forged by open-die methods. Similarly, forgeries no more than a few inches in maximum dimension are also produced in open dies. An open-die forging may weigh as little as a few kilograms or as much as 540 Mg (600 tons).

Shapes

Highly skilled hammer and press operators, with the use of various auxiliary tools, can produce relatively complex shapes in open dies. However, the forging of complex shapes is time consuming and expensive, and such forgeries are produced only under unusual circumstances. Generally, most open-die forgings can be grouped into four categories: cylindrical (shaft-type forgings symmetrical about the longitudinal axis), upset or pancake forgings, hollow (including mandrel and shell-type forgings), and contour-type forgings. Some examples of the various shapes generated are:

- Rounds, squares, rectangles, hexagons, and octagons forged from ingots, concast material, or billet stock (Example 1), in order to develop mechanical properties that are superior to those of rolled bars or to provide these shapes in compositions for which the shapes are not readily available as-as-rolled products. These shapes are usually forged in lengths of 3 to 5 m (10 to 16 ft) and then sawed to obtain desired multiple lengths
- Hub forgings that have a small diameter adjacent to a large diameter (Example 2). Hub forgings are machined into gears, pulleys, and similar components of machinery
- Spindle, pinion gear, and rotor forgings (Examples 3 and 4). These forgings are for shaft-like parts and have their major or functional diameters either in the center or at one end, with one or more smaller diameters extending from one or both sides of the major diameter in shaft-like extensions
- Simple pancake forgings, made by upsetting a length of stock. Finished parts made from these forgings include gears, wheels, and milling cutter and tubesheet blanks
- Forged and pierced blanks, for subsequent conversion to rolled or splayed-forged rings (see Examples 5 and 6). When saddle forging is used to produce symmetrical forgings, the forging process includes expanding in the tangential direction by working on a loose-fitting mandrel
- Mandrel forgings to produce symmetrical, long, hollow forgings. The forging process includes expanding in the longitudinal (axial) direction by working on a tight-fitting mandrel (Example 7)
- Various basic shapes that are developed between open dies with the aid of loose tooling. Depending on the design of the tooling, these forgings may be of the open-die type, or they may be closed-die blocker-type forgings. Such forgings are discussed in the article “Dies and Die Materials for Hot Forging” in this Volume.
- Contour forgings, such as turbine wheels and pressure vessel components with extruded nozzles and bottleneck-shaped forgings (see the section “Contour Forging” in this article)

Hammers and Presses

Because the length of the hammer ram stroke and the magnitude of the force must be controllable over a wide range throughout the forging cycle, gravity-drop hammers and most mechanical presses are not suitable for open-die forging. Power forging hammers (air or steam driven) and hydraulics presses are most commonly used for the production of open-die forgings that weigh up to 4.5 Mg (5 tons). Larger forgings are usually made in hydraulic presses. Further information on hammers and presses is available in the article “Hammers and Presses for Forging” in this Volume.

Dies

Most open-die forgings are produced in a pair of flat dies—one attached to the hammer or to the press ram, and the other to the anvil. Swage dies (curved), V-dies, V-die and flat-die combinations, FM (free from Mannesmann Effect) dies and FML (free from Mannesmann Effect with low load) dies are also used. The Mannesmann Effect refers to a tensile stress state as a result of compressive stresses in a perpendicular orientation. These die sets are shown in Fig. 1. In some applications, forging is done with a combination of a flat die and a swage die. The dies are attached to platens and rams by either of the methods shown in Fig. 1(a) and (b). Figure 1 also shows several types of dies that are held on the anvil manually by means of handles similar to those on the cutting and fullering bars shown in Fig. 4. Information on die materials, die parallelism, and die life for open-die forging is presented in the article “Dies and Die Materials for Hot Forging” in this Volume.

Auxiliary Tools

Mandrels, saddle supports, sizing blocks (spacers), ring tools, bolsters, fullers, punches, drifts (expansion tools), and a
wide variety of special tools (for producing shapes) are used as auxiliary tools in forging production. Because most auxiliary tools are exposed to heat, they are usually made from the same steels as the dies.

Saddle Supports. An open-die forging can be made with an upper die that is flat, while the lower die utilizes another type of tool. Two or more hammers or presses and die setups are often needed to complete a shape (or operations are done at different times in the same hammer or press by changing the tooling). For example, large rings are made by upsetting the stock between two flat dies, punching out the center, and then saddle forging (Examples 5 and 6). As shown in Fig. 2, the lower die is replaced by a saddle arrangement that supports a mandrel inserted through the hollow workpiece.

Sizing Blocks. A sizing block can be used between the mandrel and the ram to prevent the cross section of the workpiece from being forged too thin. Most state-of-the-art presses have automatic sizing or thickness controls.

Bolsters. The open-die forging of hubs requires a bolster (Example 2). Hub forgings are forged to the shape shown in Fig. 13, Operation 2. A bolster is then placed on the lower die, the smaller diameter of the workpiece is inserted into the bolster, and the larger diameter is upset. Depending on the size and shape of the workpiece, it may be necessary to remove the lower die and to use the anvil to support the bolster.

Ring Tools. A tongthold can be retained on a forging so that the forging can be more easily handled after upsetting, as shown in Fig. 3. A ring tool with a center opening is placed on the workpiece. During the upsetting, the hot work metal at the ring tool opening is protected from being upset, and it is back extruded to a tongthold with a length equal to the thickness of the ring.
tool. Alternatively, the tonghold can be forged on one end of the workpiece prior to upsetting; a hole in the lower die protects the tonghold during the upsetting operation. Fullers are required for starting stepped-down diameters on workpieces such as spindle forgings. They are often used in pairs (see Example 3). Figure 4 illustrates some of the commonly used cutting and fullering bars.

Mandrels are used to produce long, symmetrical, hollow forgings. The workpiece is elongated in the longitudinal (axial) direction while positioned on the mandrel and is worked between the top flat die and bottom V-die combination (Example 7). The mandrel has a slight taper on the outside diameter in order to facilitate removal of the finished hollow forging. In addition, a 25 to 50 mm (1 to 2 in.) hole in the center helps to provide water cooling of the mandrel inside diameter in order to avoid the hot forge welding of the workpiece onto the mandrel. The length and outside diameter of the mandrel bar is governed by the inside diameter and the length of the hollow forging.

Punches. To make holes, punches are placed on the hot workpiece and are driven through, or partly through, by a ram. A hole can also be made by punching from both sides (Example 5). Relatively deep holes can be produced by punching from both sides until only a thin center section remains.

Hot trepanning is done to produce a hole through the center of a large cross section, large mass workpiece. A circular cutter having an outside diameter of the same size as the desired hole and measuring about 25 mm (1 in.) in wall thickness and about 203 mm (8 in.) in height is initially positioned and pushed into the hot workpiece by the top die while the workpiece is sitting on a lower die with a hole in it. The hot-trepanning operation is continued by pushing the followers through the workpiece.

These followers have the same inside diameter as the cutter, but a slightly smaller outside diameter (~13 mm, or ½ in. smaller). The followers are locked into position prior to being pushed into the hot workpiece. The length of the followers varies and is based on the length of hot trepanning desired. This hot-trepanning length could be made up by using one or more multiple followers.

**Handling Equipment**

The handling of workpieces is often more difficult in open-die forging than in closed-die forging. Usually, the workpieces are heavier, and they must be repositioned many times during the forging cycle.

In practice, small forgings weighing up to about 45 kg (100 lb) are handled with tongs by the forging crew, or a small floor manipulator can be used. Larger forgings weighing up to about 910 kg (2000 lb) are usually handled by floor manipulators and, less frequently, by special tongs or porter bars. Forgings weighing more than 910 kg (2000 lb) are handled by large mobile manipulators, by manipulators on tracks, or by porter bars in conjunction with overhead cranes. Ingots that are forged into bars or billets are usually handled by a balancing porter bar and an overhead crane.

**Electric overhead travelling cranes with special lifting devices are used to transport billets and semifinished forgings to and from the heating furnaces and to and from the forging machines. At the forging machine, several different types of equipment are available for moving the workpiece. One is an electric crane that 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 pins, passes over the drum and moves with it. This device is also called a rotator.

**Porter Bars.** Another handling device is the porter bar. It has a hollow end that is shaped to fit the sinkhead of the billet being forged or some portion of the workpiece.

**Production and Practice**

Stock for smaller open-die forgings is usually prepared by cold sawing to a length
that is computed to contain the required weight and volume of material. Allowance is made for dimensional variations in the cross section of the billet stock. Stock is sometimes sheared to length, but the upper limit that can be sheared is about 152 mm (6 in.) square or round. Large open-die forgings are commonly forged from ingots. Large ingots are sometimes used to produce two or more forgings in which the individual forgings are parted by cutting (cold or hot), burning, or machining. When ingots are used, an additional weight allowance is usually provided for the removal of end defects, such as shrinkage, porosity, and pipe.

**Blocking and Upsetting.** The first step in the forging process usually consists of elongating the ingot along its longitudinal axis. This process has been referred to as blocking, cogging, solid forging, elongation forging, or drawing out. However, some forgings—in particular, small electroslag remelted and vacuum arc remelted ingots, which are usually free from solidification porosity—are direct upset forged. Upsetting is a hot-working process done with the ingot axis in a vertical position under the press. This operation decreases the axial length of the ingot and increases its cross section. As discussed later in this article, both blocking and upsetting are sometimes used to produce certain forging shapes.

**Heating practice** for the forging stock is the same in open-die and closed-die forging (see the article “Closed-Die Forging in Hammers and Presses” in this Volume). Large ingots, blooms, or billets of alloy steels such as AISI 4340 should be heated carefully in order to minimize decarburization and to avoid cracking due to rapid heating. Preheating can be used to minimize cracking.

Dye temperature is usually less critical in open-die than in closed-die forging. Flat dies are usually not preheated (forgings composed of aluminum and nonferrous alloys are the exception). Swage or V-dies, if they have become completely cold (as from a weekend shutdown), are sometimes warmed, particularly for hammer operations. Die heating or warming can be accomplished by closing the dies on slabs of heated steel (warners). Any cooling of the open dies is incidental and results from the compressed air or high-pressure water spray used in descaling the forging in process or from the ambient temperature of the forge shop.

**Lubrication** is usually not required for open-die forging except in those loose tooling applications in which metal flow is problematic. Lubrication is sometimes used for the forging operation in order to eliminate the dead area (or mull) formed before the dies (this is especially critical for materials that cannot be refined through phase transformation, such as austenitic stainless steels, aluminum alloys, and nickel-base alloys). Lubrication is also used in mandrel forging and in contour forming to improve metal flow (such as for nozzle extrusion and certain pressure vessel components that are contour formed).

**Descaling of the workpiece is done by** bypassing and blowoff, as in some closed-die operations (see the article “Closed-Die Forging in Hammer and Presses” in this Volume). Best practice includes the use of compressed air to blow away the scale as it breaks off. High-pressure water is also sometimes used to loosen scale, especially at hard-to-reach locations, such as the inside diameter of a mandrel forging. Failure to remove the scale causes it to be forged in, resulting in pits and pockets on the forged surfaces. The total amount of scale formed in open-die forging is usually greater than in closed-die forging because the hot metal is exposed to the atmosphere for a longer time; that is, open-die forgings usually require more forging strokes and sometimes require reheating. Metal loss through scaling usually ranges from 3 to 5%. For certain types of forgings, such as back extrusions, the descaling time is critical in terms of forgeability because the temperature of the forging can drop dramatically during prolonged descaling, resulting in a loss in forgeability.

**Hammer/Press Practice.** Unlike closed-die forging, in which the metal in the entire forging is worked at the same time, open-die forging involves the working of only a portion of the forging. Therefore, a given hammer or press can produce open-die forgings of greater weight and size than a hammer or press of equivalent rating in closed-die work, but at a lower production rate.

Hammer and press practice vary considerably from one open-die shop to another. For example, in one shop, a hammer may make three times as many blows per hour as a similar hammer in another shop, yet each shop may be using the equipment efficiently in terms of the nature of the work, the capacity of the furnaces and other equipment, and the size of the crew. In addition, different shops may make the same shape in different steps. For instance, in Example 5, a square billet was pancaked, shingled to an octagonal shape, and then rounded. Another shop might make this disk by breaking the corners of the square billet to obtain an octagonal shape, which would then be pancaked to a disk.

**Ingot Structure and Its Elimination**

Ingot is extensively used as forging stock in the open-die forging of large components, such as the turbine rotor described in Example 4. Whenever ingots are used, it is desirable (and often mandatory) to adopt a forging procedure that will remove the cast structure (ingotism) in the finished forging. Figure 6 shows a schematic cross section of a large ferrous forging ingot. Because of the large diameter of heavy forging ingots (up to 4.1 m., or 160 in.), the solidification process is extremely slow, often taking as long as 2 to 3 days. Unfortunately, the slow cooling rate causes considerable macrosegregation, especially in the ingot center toward the top of the ingot. Consequently, the center of the ingot must be mechanically worked during the forging operation to redistribute the segregated elements and to heal internal porosity (Ref 2).

The segregated regions are usually associated with a coarse dendritic structure; therefore, breaking up these regions by using hot deformation leads to refined microstructures. Compression of the dendritic arms reduces the local diffusion distance, which can enhance homogenization during subsequent heat treatment. Repeated hot deformation also causes grain refinement through static and/or dynamic recrystallization of the austenite. Finer austenitic grain sizes promote finer microstructures during subsequent transformation to ferrite, pearlite, and bainite or martensite or both. Finer microstructures lead to more uniform mechanical properties and, in general, improved tensile properties coupled with greater toughness. However, nonuniform hot deformation can lead to undesirable duplex microstructures, that is, mixed fine and coarse grain sizes/transform products. Segregated regions containing higher aluminum concentrations can also lead to nonuniform recrystallization and grain growth.

Various approaches are available for minimizing the undesirable effects of segregation. In some forgings, the centerline is actually removed from the finished product in the form of a core bar by machine trepanning. This is permissible for some symmetrical rotating machinery; however, many forgings are not symmetrical, and the center region cannot be removed. In these cases, the thermal and thermomechanical treat-
ments must be optimized in order to redistribute the solute elements. Long homogenization treatments at temperatures approaching 1290 °C (2330 °F) are frequently conducted to allow some diffusion of alloying elements. However, redistribution (homogenization) of the substiutional solid-solution elements, such as manganese, silicon, nickel, chromium, molybdenum, and vanadium, would require several weeks at temperature, which is far too long to be economically feasible. The other alternative is to put as much hot work as possible into the segregated regions.

Hot deformation in the center of the ingot is enhanced when there is a temperature gradient from the surface to the center of the ingot (Ref 3-5). Under certain circumstances in production, ingots are deliberately air cooled from the soaking temperature before forging. The cooler surface regions, having a higher flow stress, translate the forces of the draft (percentage of reduction) to the center of the ingot, thus increasing centerline consolidation.

Transformation of the initial cast structure into a fully wrought structure requires extensive hot working in the form of successive reduction of cross section, enlargement of cross section by upsetting, and an additional reduction of cross section. Therefore, in Example 4, the principal section of the rotor forging was enlarged by upsetting in Operation 3, Position 1, and was then reduced by almost 30% in Operation 3, Position 2. This seemingly circuitous procedure helps to break up the cast structure and to eliminate ingotim throughout the section.

The development of substantial deformation at the center of the ingot, bloom, or billet to break up the cast structure and to heal any porosity depends on the press capacity and on the relationship between die width and stock height (w/d). If the press capacity is small and if die width is narrow, the penetration, or depth of deformation, will be small. The width of the draw-out dies should be at least 60% of the stock height in order to ensure adequate centerline deformation (Ref 6). The die width and depth of penetration (percentage of the reduction, or draft size) have a significant influence on the size of the press used for open-die forging. Although billets cut from wrought bars are normally free of ingotim, they can be given additional hot working (more than the minimum required to develop contour) in order to refine the structure and to impose a more desirable flow pattern than that inherent in the original billet or in the wrought product.

**Forgability**

Metals and alloys vary in forgeability from highly forgeable to relatively brittle. Relative forgeability is indicated below for metals and alloys used in open-die forging:

- **Most forgeable**
  - Aluminum alloys
  - Magnesium alloys
  - Copper alloys
  - Stainless steel alloys
  - Maraging steels
  - Austenitic stainless steels
  - Nickel alloys
  - Stainless PH stainless steels
  - Titanium alloys
  - Iron-base superalloys
  - Cobalt-base superalloys
  - Niobium alloys
  - Tantalum alloys
  - Molybdenum alloys
  - Nickel-base superalloys
  - Tungsten alloys
  - Beryllium alloys

- **Least forgeable**

**Deformation Modeling**

The ability to predict material flow, energy requirements, and forming loads is very helpful in facilitating design or operations in open-die forging. The maximum force developed in forging will determine the size of the hammer or press required and will set the limits for the elastic distortion permissible for the forging equipment to be used. The energy requirement will determine whether a given forging can be made on an available hammer or press. The design of a forging practice for open-die forging involves the selection of certain parameters to be used, such as die dimensions and shapes, amount of reduction, ingot shape, temperature gradient, ram velocity, and pass sequence. The development of forging practices through full-scale production trials is expensive and time consuming. In addition, only minimal internal strain data can be collected. Therefore, both mathematical and physical modeling are applied to provide design criteria and to gain a better understanding of open-die forging operations.

**Mathematical Modeling.** The forging process can be understood with the aid of a series of theoretical approaches in the field of metalworking. Elementary plasticity theory (Ref 7, 8) is used to provide a series of relationships that can yield an estimation of the force and energy requirements for such forging operations as upsetting and blocking. If the correct coefficient of friction can be selected, such relationships permit an accurate estimation of the force and energy requirements (Ref 9).

Slip-line theory is used to obtain deformation information relating to localized stress states. This permits precise statements to be made concerning stress states in the center of the forged ingots (Ref 10). The disadvantage of this theoretical method lies in its assumption that the metal used in hot forging behaves as an ideal rigid-plastic material, which is usually not the case. Therefore, this technique is incapable of describing such an effect as the influence of bite displacement on stress state. On the other hand, the upper bound method seeks to compensate for the lack of information on the actual material flow by assuming a velocity field and by optimizing the performance without stress consideration (Ref 11, 12). The disadvantage of this method is that the assumed velocity field becomes extremely complex if all of the kinematic parameters are to be satisfied.

Because precise knowledge of the stress and deformation history of a workpiece is necessary to determine its real formability during forging, the computational procedure of the finite-element method appears to have the best prospects for simulating forging processes. The use of the finite-element method as a numerical analysis tool has dominated this field and remains the most popular method for deformation modeling. In two dimensions, a variety of problems can be explained and simulated, such as the progress of centerline penetration or comparisons between two forging processes (Ref 13), the design of upsetting and ring compression tests (Ref 14-17), and the influence of selected forging parameters on the final quality of the forge products (Ref 18, 19).

In general, the theoretical methods used to predict forces and other performance variables are based on certain assumptions (ideal conditions) that deviate to some degree from the actual forging process. In addition, their reliability and effectiveness are strictly dependent on how smoothly a forging process proceeds. However, as soon as the workpiece is of any complexity (that is, any deviation from the ideal), this method fails. Therefore, calculated values are usually considerably higher or (depending on the conditions and forging process) lower than the measured values. One reason for this discrepancy is related to the temperature gradients developed during forging. In addition, strain rates vary during various parts of the forging stroke, and it is difficult to choose a true representative strain rate and corresponding yield stress at the estimated average temperature. For all of these reasons, calculation of the force and energy requirements on a theoretical basis is still in its infancy.

Both private and government-sponsored research efforts are making progress toward the goal of providing modeling techniques that are useful to the open-die forging industry. In addition, heuristic or artificial-intelligence expert systems are being developed to assist new open-die technology processes and designs. More detailed information can be found in the Section "Computer-Aided Process Design for Bulk Forming" in this Volume.
Physical Modeling. Because of the above disadvantages associated with the use of theoretical modeling methods, physical modeling is often employed. Physical modeling can often provide deformation information that would otherwise be inaccessible or too expensive to obtain by other techniques; this makes physical modeling a powerful tool for the study of forging practices. As its name implies, physical modeling involves changing some physical aspect of the process being studied, such as the size or the material being deformed. In doing so, however, some properties of the original material or the process or both are sacrificed in order to bring the relevant properties more clearly into focus. Nonetheless, if the modeling material employed is homogeneous, isotropic, and obeys the laws of similitude and if the boundary conditions, especially friction and tool geometry, are met in the physical modeling experiment, then excellent qualitative and sometimes quantitative results can be achieved (Ref 20).

Among the various metallic (steel, aluminum, and lead) and nonmetallic (wax and plasticine) modeling materials, plasticine, a particular type of modeling clay, is probably the most widely used for studying open-die press processes (Ref 21-29). There are several advantages to using plasticine as a modeling material. First, plasticine is readily available, inexpensive, and nontoxic. Second, plasticine deforms under low forces at room temperature, thus considerably simplifying the experimentation and allowing the use of low-cost tooling and equipment. Third, two-color models are feasible for studying internal material flow. Fourth, plasticine exhibits dynamic deformation properties that are similar to those of steel at high temperature. Lastly, plasticine is able to provide quantitative information with respect to the deformation distribution by means of specially designed layered specimens.

Physical modeling with plasticine and lead is extensively used to develop processes for new products and to improve existing manufacturing techniques for better economical processes in various kinds of open-die forgings. In blocking, such parameters as die width, die configuration, die overlapping, die staggering ingot shape, temperature gradient, and draft design can be optimized to minimize the internal deformation for better structural homogeneity and soundness of material in the core of the ingot (Ref 26, 27). Figures 7 and 8 show the effects of temperature gradient and draft design, respectively, on the centerline deformation distribution for square cross-sectional ingots subjected to multiple-stroke blocking (Ref 27).

In upsetting, the influence of selected parameters such as aspect ratio, crosshead speed, ingot chuck, spreading, indenting, and dished dies versus upsetting dies on the internal deformation distribution can be effectively studied through physical modeling (Ref 28). Figure 9 shows the influence of various aspect ratios on the

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**Fig. 7** Effect of temperature gradient using scaled (Ref 21-29). Figures 7 and 8 show the effects of temperature gradient and draft design, respectively, on the centerline deformation distribution for square cross-sectional ingots subjected to multiple-stroke blocking (Ref 27).

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**Fig. 8** Effect of draft design on the compressive strain distribution. Solid line indicates compressive strain; broken line, longitudinal strain. (a) 5% reduction increments. (b) 8% reduction increments. (c) 10% reduction increments.

**Fig. 9** Effect of aspect ratio (H/D) on compressive strain distribution in plasticine ingots. A, 1.0 ratio; B, 1.5 ratio; C, 2.0 ratio.
compressive strain distribution from the top to the bottom of the upset-forged ingot (Ref 28). The influence of these blocking and upsetting parameters on void closure can be determined by providing artificial holes inside plasticine or lead ingots (Ref 29, 30).

The application of physical modeling to forged products has led to improvements in yield and quality and cost savings. Additional information is available in the Section “Computer-Aided Process Design for Bulk Forming” in this Volume.

**Examples of Production Practice**

Because of differences in equipment and operator skill, procedures for open-die forging vary considerably from plant to plant.

Fig. 10 shows typical steps in the drawing and forging of stock and in the fabrication of common shapes from billets of square, rectangular, and round cross sections. The procedures described in the following examples are typical of those used for the production of some common open-die forgings.

**Example 1: Forging a 170-kg (375-lb) Solid Cylinder in Flat Dies.** A cylinder, 241 mm (9½ in.) in diameter by 470 mm (18½ in.) in length, was forged in flat dies from 305 × 305 × 254 mm (12 × 12 × 10 in.) stock in four operations without reheating the billet (Fig. 11). The following sequence of operations was used:

*Operation 1.* The 305 mm (12 in.) square section was hammered to a 229 mm (9 in.) square section, which increased the length to 432 mm (17 in.).

*Operation 2.* The corners of the square were hammered to produce an octagonal shape approximately 229 mm (9 in.) across flats and 533 mm (21 in.) long.

*Operation 3.* The octagon was rounded by successive hammer blows as the workpiece was rotated. The cylindrical forging was then approximately 559 mm (22 in.) long.

*Operation 4.* The forging was upended and hammered lightly on both ends to flatten the bulge on the ends. This decreased the length to 470 mm (18½ in.) and increased the diameter to 241 mm (9½ in.). Additional processing details are given in the table in Fig. 11.

**Example 2: Forging a Combined Gear Blank and Hub in Flat Dies Using a Bolster.** The combined gear blank and hub forging shown in Fig. 12 was forged from
Stock preparation: Cold sawing
Stock size: 305 x 305 x 254 mm (12 x 12 x 10 in.)
Stock weight: 179 kg (395 lb)
Finished weight: 179 kg (375 lb)
Heating furnace: Gas-fired, automatic temperature control
Heating temperature: 1210 °C (2200 °F)
Forging machine: 18 kN (4000 lb) steam hammer

(a) Forging was completed in one heat.

Fig. 11 Sequence of operations in the forging of a cylindrical workpiece from square stock. Dimensions in figure given in inches.

203 x 203 x 175 mm (8 x 8 x 7/8 in.) stock in five operations, as follows.

Operation 1. The stock was forged to 178 x 178 x 254 mm (7 x 7 x 10 in.). This oblong was then forged into a belted-end cylinder about 191 mm (7 3/4 in.) in diameter and 279 mm (11 in.) in length, by being rotated and struck with successive hammer blows.

Operation 2. A stem approximately 102 mm (4 in.) in diameter and 203 mm (8 in.) in length was drawn from 64 mm (2 1/8 in.) of the 279 mm (11 in.) length.

Operation 3. The workpiece was placed vertically in a bolster, as shown in Fig. 12, Operation 3.

Operation 4. The head was flattened (upset) until it was approximately 102 mm (4 in.) thick. The forging was then removed from the bolster and rounded up in flat dies.

Operation 5. The workpiece was placed in the bolster again and forged to the dimensions shown in Fig. 12, Operation 5. The forging was fully annealed and rough machined. Additional processing details are given in the table with Fig. 12.

Example 3: Forging a Four-Diameter Spindle in Flat Dies. The four-diameter spindle forging shown in Fig. 13 was forged from 685 x 406 x 406 mm (27 x 16 x 16 in.) stock with one reheat in the following sequence of operations.

Fig. 12 Typical procedure for the forging of a gear blank and hub in open dies, featuring the use of a bolster. Dimensions in figure given in inches.

Operation 1. All but 254 mm (10 in.) of the hot stock was forged to a 337 mm (13/4 in.) square section, using a sizing block on the lower die to gage size.

Operation 2. The workpiece was turned 45°, and the 337 mm (13/4 in.) square section was flattened as shown in Position 1, Operation 2 (Fig. 13). The workpiece was rotated as the reduced portion was forged to an octagonal shape, as shown in Position 2, Operation 2. The octagon was then hammered into a round approximately 337 mm (13/4 in.) in diameter (final shape in Position 2 not shown).

Operation 3. The workpiece was placed diagonally across the lower die; 508 mm (20 in.) from the end, a 267 mm (10 1/2 in.) diam section was started by top and bottom fullers. The workpiece was rotated as the fullers were pressed into the hot steel, and a deep groove was formed around the workpiece (Fig. 13, Operation 3).

Operation 4. The 337 mm (13/4 in.) sizing block was replaced by 267 mm (10 1/2 in.) sizing block. The 508 mm (20 in.) long section was hammered first to a square, then to a octagon, and finally to a round
Operation 4. The main body of the forging was developed between a flat top die and a bottom V-die. The ends of the forging were set down to 959 mm and 1.01 m (37\% and 39\%) in. diameters, respectively, and two additional diameters were forged between these sections. The bolster section (965 mm, or 38 in., in diameter by 914 mm, or 36 in., in length) was cut away at the conclusion of this operation.

Operation 5. Finish forging developed two additional stepped sections, ranging from 470 to 889 mm (18\% to 35 in.) in diameter, at each end of the forging. Following this operation, discard sections were cut from both ends of the forging. A large discard section was removed from the end of the forging (corresponding to the bottom of the ingot) that had not been cropped during the previous operations. The finished forging was heat treated to develop optimal mechanical properties. Extensive mechanical tests were performed on specimens taken from the discard sections.

Example 5: Forging and Piercing a Blank for Forming a Ring. The forged and pierced blank shown in Fig. 15 was forged from 305 × 254 × 254 mm (12 × 10 × 10 in.) stock. The sequence of operations was as follows.

Operation 1. Heated stock was placed vertically on a flat die. The 305 mm (12 in.) height was reduced to 152 mm (6 in.) and the 254 mm (10 in.) square cross section was increased to 356 mm (14 in.) square. The workpiece was repositioned and hammered, first to a hexagonal, next to an octagonal, and then to a round section 406 mm (16 in.) in diameter by 152 mm (6 in.) in length.

Operation 2. The workpiece was flattened to a 75 mm (3 in.) thick, 559 mm (22 in.) round, and a tapered plug was centered and hammered in.

Operation 3. The hot workpiece was rotated and hammered on its circumference to flatten the edge, which bulged from previous hammering, and to loosen the plug.

Operation 4. The workpiece was positioned as shown in Fig. 15, Operation 4, and the 127 mm (5 in.) diam hole was completed by piercing from the opposite side. The pierced blank was saddle forged to a ring on a mandrel, following the technique shown in Fig. 2 (see also Example 6).

Forging of Rings. Rings are often rolled from forged and pierced blanks (see the article "Ring Rolling" in this Volume); however, when rolling is precluded (because of small quantities, short delivery time, or other reasons), saddle forging (Fig. 2) is often used. Typical procedures for producing rings by this method are described in the following example.

Example 6: Saddle Forging a 1.02 m (40 in.) OD Ring From a 559 mm (22 in.) OD Blank. A 1.02 m (40 in.) OD ring was saddle forged in a 6670 N (1500 lb) steam
Fig. 15 Sequence of operations in the forging and piercing of a circular blank. Dimensions in figure given in inches.

Hammer from a 559 mm (22 in.) OD blank produced as described in Example 5 and shown in Fig. 15. Flattening operations were done at suitable intervals to reduce the ring to a 50 mm (2 in.) thickness. Saddle forging was done as follows (Fig. 16).

Operation 1. The blank was heated to 1230 °C (2250 °F) and forged to the dimensions shown in Fig. 16, Operation 1, by alternate saddle forging and flattening.

Operation 2. The 711 mm (28 in.) OD ring was reheated to 1230 °C (2250 °F) and forged by the same technique used in Operation 1 to produce a 914 mm (36 in.) diam ring.

Operation 3. The 914 mm (36 in.) OD ring was reheated to 1230 °C (2250 °F) and saddle forged and flattened as needed to obtain a 50 mm (2 in.) thickness, a 1.02 m (40 in.) outside diameter, and a 762 mm (30 in.) inside diameter.

Example 7: Mandrel Forging a Long Hollow Piece on a 40.9 MN (4600 tonf) Hydraulic Press. Mandrel-forging technique is utilized to produce a long, hollow, cylindrically symmetrical piece. The outside diameter of the production piece was 1.32 m (52.0 in.). The average inside diameter was 914 mm (36.0 in.). The total overall length was 7.0 m (23.0 ft) with a 1.59 m (62.75 in.) diam by 482 mm (19.0 in.) long flange included on one end of the piece. The flange drops to a 1.45 m (57.0 in.) diameter, which tapers to the 1.32 m (52.0 in.) body diameter over a 229 mm (9.0 in.) length.

Operation 1. The 2.11 m (83 in.) diam, 78,900 kg (174,000 lb) ingot of AISI 4130 grade steel was used as the starting stock. It was heated to the forging temperature and straight forged (saddened) to 1.57 m (62.0 in.) diam size.

Operation 2. Top and bottom ingot discs were taken by flame cutting to yield a slug of 1.57 m (62.0 in.) in diameter and 3.20 m (126.0 in.) in length.

Operation 3. The slug was upset forged by positioning it vertically under the press. The 3.20 m (126.0 in.) dimension was reduced to 3.15 m (80.0 in.).

Fig. 17 Illustrations showing turbine wheel formed by using contour forging method.

Fig. 18 Illustration of nozzle extrusion, a complex contour forging method. (a) Punch position before extrusion. (b) Punch position after extrusion.
Open-Die Forging

Operation 6. The piece was mandrel forged on a tapered mandrel (0.8 to 1 m, or 33 to 39 in., in diameter) using the top flat die and bottom V-die. Mandrel forging caused the metal to move in the longitudinal (axial) direction, thus producing the desired part.

Contour Forging

Open-die contour or form forging requiring the use of dedicated dies has been successfully accomplished for carbon, alloy, and stainless steels as well as for superalloys. Contour forging can be advantageous under such circumstances as the following:

- Enhancement of grain flow at specific locations, when demanded by product application
- Reduction of the quantity of starting material; this is especially critical when using expensive materials such as stainless steels and superalloys
- Reduction of machining costs; this is critical when machinability or excessive material removal are factors

Turbine Wheel Forging. Turbine wheels, which are commonly 2.54 m (100 in.) in diameter, are forged by first upsetting a block of steel and then contour forging to provide the thick hub and thin rim sections (Fig. 17). This is done using a shaped (contoured) bottom die, which supports the entire workpiece, and a shaped partial top (contoured swing) die. Successive strokes are taken with the top die as it is indexed around the vertical centerline of the press. The partial top die minimizes the force required to deform the metal, yet produces the desired forging envelope.

Nozzle extrusion is a more complex contour-forging method (Fig. 18). Nozzle extrusions are commonly used for thick-wall vessels in cases in which the cost of extruding the nozzle shape offsets the cost and quality risk factors involved in producing the shell and the nozzle as a weldment. The tooling consists of a shaped bottom die and a punch. The punch is forced through a machined pilot hole in the workpiece. The material conforms to the shape of the bottom die and is extended forward to form the nozzle. Two possible methods of producing a shell section with a nozzle are shown in Fig. 19. Design engineers prefer the nozzle extrusion technique over the welded nozzle because of the superior grain flow characteristics, toughness, and favorable costs associated with the extrusion process.

Pressure vessel head forgings can be produced from either forged or rolled plate by either of two methods. In the first method, full male and female dies are used to develop a dome shape (Fig. 20a). In the second method, a partial male die and a full female die are used to produce a dome shape (Fig. 20b). The second method, although requiring more forging strokes than the first method (the top die is swung in incremental positions for each stroke), reduces the press load per stroke. Therefore, larger dome shapes can be made by this technique. In addition, if required, smaller presses can be used to make the dome shapes (press capacity will determine the appropriate swing die width that can be used).

Bottleneck-shaped forgings are made as doubles from a straight forged bar (Fig. 21). For example, 292 mm (11.5 in.) radius contour dies are set down 165 mm (6.5 in.) to achieve the small diameter of 254 mm (10.0 in.) from the large diameter of 584 mm (23.0 in.). In order to generate axial movement during the forging process, the flat die width must be a minimum of 50 mm (2.0 in.) less than the set down dimension. In addition, the die radius adjacent to the flat and the contour should be a minimum of 38 mm (1.5 in.) to enhance axial metal flow and to minimize material lapping.

Forging quality is best achieved using a 17.8 MN (2000 tonf) hydraulic press by positioning the die to the set-down mark as shown in Fig. 21 and manually or mechanically rotating the workpiece in 10° to 15° increments using not greater than 25 mm (1 in.) drafts. The process is continued by working from side to side, keeping the die tight to the contour, while exercising caution to avoid lapping on the contour.

Allowances and Tolerances

To make certain that forgings can be machined to correct final measurements, it is necessary at the forging stage to establish allowances, tolerances, and specifications for flatness and concentricity.
### Table 1: Allowances and tolerances for as-forged shafts and bars

Allowance is added to rough-machined dimension to obtain forged dimension. Tolerances are the variations permitted on forged dimensions.

<table>
<thead>
<tr>
<th>Rough-machined diameter or width, mm</th>
<th>Allowance for overall rough-machined length, mm (in.), of:</th>
<th>Over 527-762 (6-30)</th>
<th>Over 762-1520 (30-60)</th>
<th>Over 1520-2290 (60-90)</th>
<th>Over 2290-3050 (90-120)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over 25.75 (1-3)</td>
<td>+3.2, -0.4 (+6%, -1%)</td>
<td>9.5 (1%)</td>
<td>11.1 (1%)</td>
<td>12.7 (2%)</td>
<td></td>
</tr>
<tr>
<td>Over 75.15 (3-6)</td>
<td>+3.2, -0.6 (+6%, -1%)</td>
<td>11.1 (1%)</td>
<td>13.4 (2%)</td>
<td>15.9 (3%)</td>
<td></td>
</tr>
<tr>
<td>Over 125.229 (6-9)</td>
<td>+3.2, -0.6 (+6%, -1%)</td>
<td>12.7 (2%)</td>
<td>14.9 (3%)</td>
<td>17.4 (4%)</td>
<td></td>
</tr>
<tr>
<td>Over 229.305 (9-12)</td>
<td>+3.2, -0.6 (+6%, -1%)</td>
<td>18.4 (3%)</td>
<td>19.1 (3%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Over 305.457 (12-18)</td>
<td>+4.8, -0.6 (+9%, -1%)</td>
<td>21.4 (3%)</td>
<td>23.4 (4%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Over 547.610 (18-24)</td>
<td>+4.8, -0.6 (+9%, -1%)</td>
<td>25.4 (4%)</td>
<td>27.4 (5%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Over 677.610 (24-30)</td>
<td>+4.8, -0.6 (+9%, -1%)</td>
<td>29.4 (5%)</td>
<td>31.5 (6%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Over 945.610 (30-40)</td>
<td>+6.4, -0.6 (+12%, -1%)</td>
<td>33.4 (6%)</td>
<td>35.4 (7%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Over 1095.620 (40-50)</td>
<td>+6.4, -0.6 (+12%, -1%)</td>
<td>37.4 (7%)</td>
<td>39.4 (8%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Over 1250.630 (50-60)</td>
<td>+6.4, -0.6 (+12%, -1%)</td>
<td>41.4 (8%)</td>
<td>43.4 (9%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Allowances and tolerances for as-forged shoulder shafts

A shaft forging that has more than one cross-sectional dimension is illustrated at right. To compute allowances and tolerances for a forging of this type, use the following method:

1. For the largest diameter, take the allowance given in the table above, using the overall length of the forging.
2. For each smaller diameter, take allowance given in table above, using overall length of forging, and average this with allowance for largest diameter. Use next-larger allowance wherever calculated average is not found.
3. Allowance on each end of the overall length is the value indicated in the first column for the largest diameter or the value indicated on the top line for the overall length, whichever is greater. Allowance on each end of intermediate lengths is same as allowance on each end of overall length.
4. Tolerance is as indicated in the table above for the allowance that is applied.

Applying the rules given above to the forging illustrated at right:

#### Allowances and tolerances for diameters

<table>
<thead>
<tr>
<th>Machined dimension, mm (in.)</th>
<th>Allowance, mm (in.)</th>
<th>Forging dimension, mm (in.)</th>
<th>Tolerance on forging, mm (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>318 (12)</td>
<td>25.4 (1)</td>
<td>343 (133%)</td>
<td>±6.4 (±6%)</td>
</tr>
<tr>
<td>241 (9.5)</td>
<td>22.2 (11*1 + 25.4 + 2% (16% + 2%))</td>
<td>264 (10%)</td>
<td>+6.4, -4.8 (+6%, -1%)</td>
</tr>
<tr>
<td>165 (6.5)</td>
<td>22.2 (11*1 + 25.4 + 2% (16% + 2%))</td>
<td>187 (7%)</td>
<td>+6.4, -4.8 (+6%, -1%)</td>
</tr>
<tr>
<td>127 (5)</td>
<td>22.2 (11*1 + 25.4 + 2% (16% + 2%))</td>
<td>149 (57%)</td>
<td>+6.4, -4.8 (+6%, -1%)</td>
</tr>
</tbody>
</table>

#### Allowances and tolerances for ends

| Table allowance for 2490 mm (98 in.) length | 12.7 mm (½ in.) |
| Table allowance for 318 mm (12 in.) diameter | 19.1 mm (¾ in.) |
| End allowance applicable (point 3 above) | 19.1 mm (¾ in.) per end |
| Tolerance on 19.1 mm (¾ in.) end allowance | 9.5 mm (⅛ in.) on total length |

(a) From the table, for allowances of 23.4 and 22.2 mm (1 and 3/8 in.). (b) Because product is not in the table, the next-larger allowance is used (as noted in item 2 in the list of instructions at left above). Dimensions in figure given in inches.
Allowance. In open-die forging, the allowance defines the amount by which a dimension is increased in order to determine its size at an earlier stage of manufacture. An allowance is added to a finish-machined size. Similarly, an additional allowance is added to a rough-machined dimension to determine the forged size. These allowances provide enough stock to permit machining to final dimensions.

The stock provided for machining increases the weight of the forging at earlier stages of manufacture. The weight of the additional metal and the machining operations necessary to remove it increases the cost of the finished part. Consequently, the allowances specified for each step of manufacture should be kept as small as practical while still maintaining enough metal so that all dimensions of the finished part can be readily achieved with normal production techniques.

Table 1 shows allowances added to rough-machined dimensions of straight round, square, rectangular, or octagonal bars of uniform cross section. The allowance increases as diameter (or section width) and length increase. Table 1 also explains how allowances are determined for open-die forgings with more than one cross-sectional dimension.

Under precisely controlled conditions and with state-of-the-art thickness-controlled presses manned by highly skilled operators, it may be possible to forge somewhat closer to rough-machined dimensions; however, such a decrease in allowances must be carefully controlled to avoid machining problems. For example, usual practice may consist of increasing the allowance for critical applications in which all decarburization must be removed during rough machining. Under these conditions, 6.4 mm (1/4 in.) on a diameter or cross section (3.2 mm, or 1/16 in., per side) is usually added to the allowance given in Table 1.

Tolerance describes the permissible variation in a specific dimension. Tolerances on allowances are given in Table 1. Tolerance is approximately one-fourth (plus or minus) the allowance.

Flatness and concentricity for a forging are usually negotiated between the forge shop and the customer. However, some users of open-die forgings have established specifications. For example, one user specifies that for pancake forgings up to 610 mm (24 in.) in diameter eccentricity or out-of-roundness shall not exceed 6.4 mm (1/4 in.) and flatness shall be within 4.8 mm (1/8 in.). For pancake forgings somewhat larger than 610 mm (24 in.) in diameter, eccentricity or out-of-roundness shall be no more than 9.5 mm (3/8 in.), and flatness shall be within 6.4 mm (1/4 in.).

Safety

In open-die forging, as in other types of forging operations, safe practices must be observed when handling materials and operating equipment. More information on safety in a forging facility is available in the article “Hammers and Presses for Forging” in this Volume.

REFERENCES

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![Fig. 21](Image) Contour forging of a straight forged bar to form a double bottleneck-shaped workpiece. (a) Original 320 kg (700 lb) bar. (b) Contour-forged, 205 kg (450 lb) finished workpiece.
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