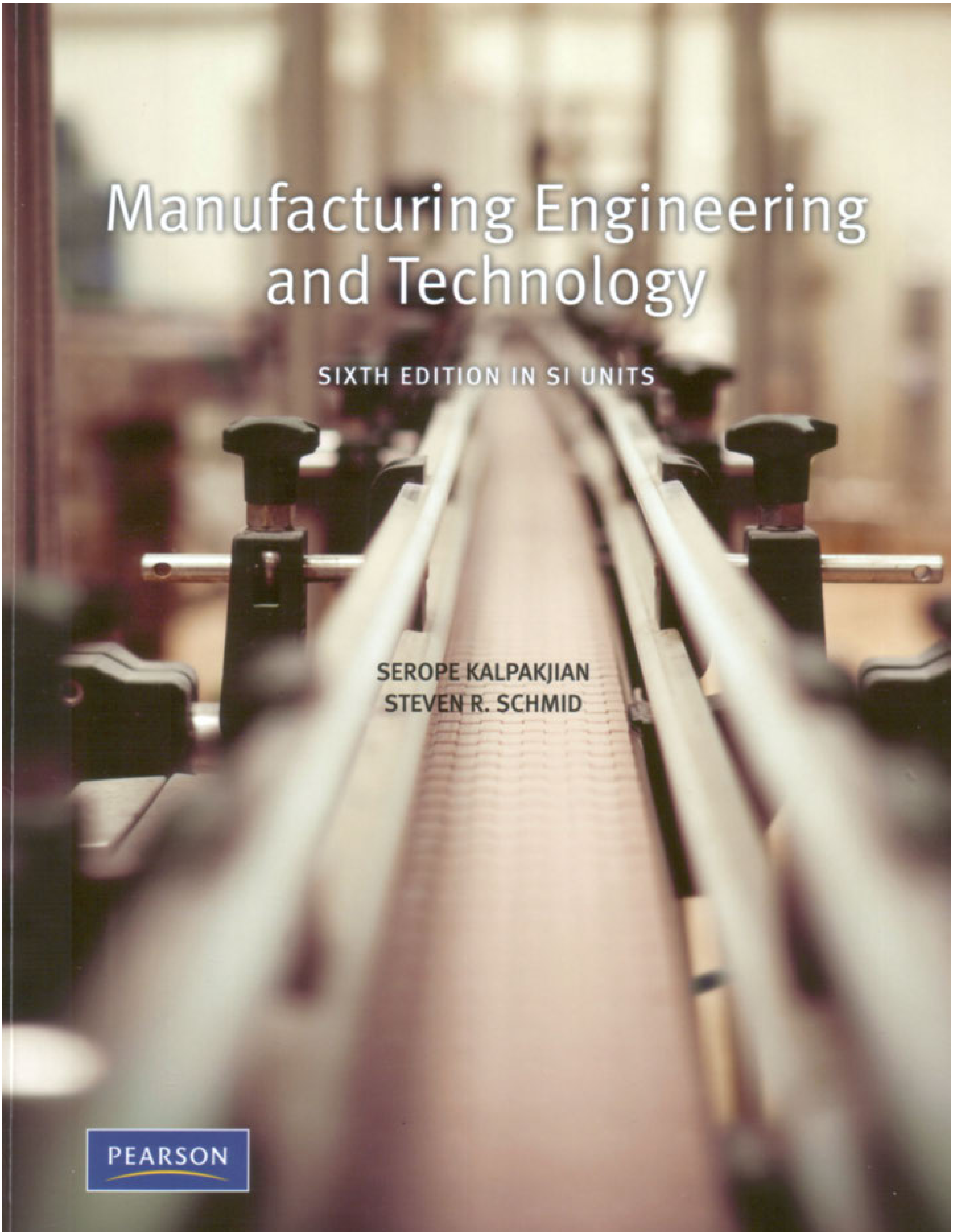
Manufacturing Engineering and Technology

SIXTH EDITION IN SI UNITS

SEROPE KALPAKJIAN
STEVEN R. SCHMID

PEARSON



Metal-Forging Processes and Equipment

CHAPTER 14

- This chapter describes the fundamentals of forging and related processes, including design and economic considerations.
- Open-die forging operations for producing simple shapes are discussed first, followed by impression-die and closed-die forging operations for producing more intricate shapes.
- Various forging operations, such as heading, piercing, coining, swaging, and cold extrusion, are then introduced.
- Factors involved in forging defects and die failures are explained.
- The economics of forging, as it relates to process selection, is also discussed.
- The chapter ends with a review of the design of forged parts, die design and manufacturing, and selection of die materials and lubricants in forging operations.

Typical parts made by forging and related processes: Shafts, gears, bolts, turbine blades, hand tools, dies, and components for machinery, transportation, and farm equipment.

Alternative processes: Casting, powder metallurgy, machining, and fabrication.

14.1 Introduction

Forging is a basic process in which the workpiece is shaped by compressive forces applied through various dies and tooling. One of the oldest and most important metalworking operations, dating back at least to 4000 B.C., forging first was used to make jewelry, coins, and various implements by hammering metal with tools made of stone. Forged parts now include large rotors for turbines; gears; bolts and rivets; cutlery (Fig. 14.1a); hand tools; numerous structural components for machinery, aircraft (Fig. 14.1b), and railroads; and a variety of other transportation equipment.

Unlike rolling operations described in Chapter 13 that generally produce continuous plates, sheets, strips, or various structural cross sections, forging operations produce *discrete parts*. Because the metal flow in a die and the material's grain structure can be controlled, forged parts have good strength and toughness, and are very reliable for highly stressed and critical applications (Fig. 14.2). Simple forging operations

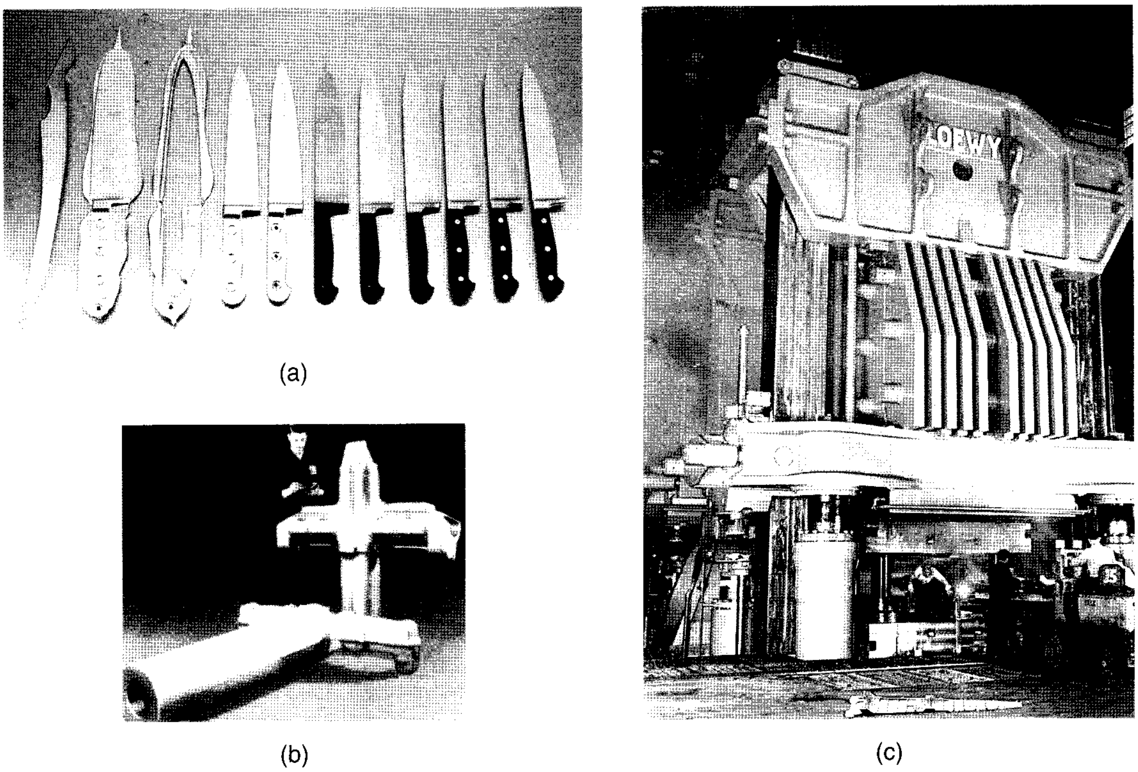


FIGURE 14.1 (a) Illustration of the steps involved in forging a knife. (b) Landing-gear components for the C5A and C5B transport aircraft, made by forging. (c) General view of a 445-MN (50,000-ton) hydraulic press. *Source*: (a) Courtesy of Mundial, LLC. (b) and (c) Courtesy of Wyman-Gordon Company.

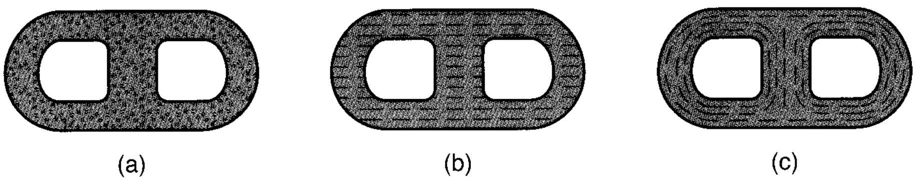


FIGURE 14.2 Schematic illustration of a part made by three different processes and showing grain flow. (a) Casting by the processes described in Chapter 11. (b) Machining from a blank, described in Part IV of this book, and (c) forging. Each process has its own advantages and limitations regarding external and internal characteristics, material properties, dimensional accuracy, surface finish, and the economics of production. *Source*: Courtesy of the Forging Industry Association.

can be performed with a heavy hammer and an anvil, as has been done traditionally by blacksmiths. However, most forgings require a set of dies and such equipment as a press or a powered forging hammer.

Forging may be carried out at room temperature (*cold forging*) or at elevated temperatures (*warm* or *hot forging*) depending on the homologous temperature; (see Section 1.8). Cold forging requires higher forces (because of the higher strength of the workpiece material), and the workpiece material must possess sufficient ductility at room temperature to undergo the necessary deformation without cracking. Cold-forged parts have a good surface finish and dimensional accuracy. Hot forging requires lower forces, but the dimensional accuracy and surface finish of the parts are not as good as in cold forging.

Forgings generally are subjected to additional finishing operations, such as heat treating to modify properties and machining to obtain accurate final dimensions and a good surface finish. These finishing operations can be minimized by *precision forging*, which is an important example of *net-shape* or *near-net-shape* forming processes. As we shall see throughout this book, components that can be forged successfully also may be manufactured economically by other methods, such as casting (Chapter 11), powder metallurgy (Chapter 17), or machining (Part IV). Each of these will produce a part having different characteristics, particularly with regard to strength, toughness, dimensional accuracy, surface finish, and the possibility of internal or external defects.

14.2 Open-die Forging

Open-die forging is the simplest forging operation (Table 14.1). Although most open-die forgings generally weigh 15 to 500 kg, forgings as heavy as 275 metric tons have been made. Part sizes may range from very small (the size of nails, pins, and bolts) to very large (up to 23 m, long shafts for ship propellers). Open-die forging can be depicted by a solid workpiece placed between two flat dies and reduced in height by compressing it (Fig. 14.3a)—a process that is also called **upsetting** or **flat-die forging**. The die surfaces also may have shallow cavities or incorporate features to produce relatively simple forgings.

The deformation of a workpiece under *frictionless conditions* is shown in Fig. 14.3b. Because constancy of volume is maintained, any reduction in height increases the diameter of the forged part. Note that the workpiece is deformed *uniformly*. In actual operations, however, there is friction, and the part develops a *barrel* shape (Fig. 14.3c)—a deformation mode also known as *pancaking*.

Barreling is caused primarily by frictional forces that oppose the outward flow of the workpiece at the die interfaces and thus can be minimized by using an effective

TABLE 14.1

General Characteristics of Forging Processes

Process	Advantages	Limitations
Open die	Simple and inexpensive dies; wide range of part sizes; good strength characteristics; generally for small quantities	Limited to simple shapes; difficult to hold close tolerances; machining to final shape necessary; low production rate; relatively poor utilization of material; high degree of skill required
Closed die	Relatively good utilization of material; generally better properties than open-die forgings; good dimensional accuracy; high production rates; good reproducibility	High die cost, not economical for small quantities; machining often necessary
Blocker	Low die costs; high production rates	Machining to final shape necessary; parts with thick webs and large fillets
Conventional	Requires much less machining than blocker type; high production rates; good utilization of material	Higher die cost than blocker type
Precision	Close dimensional tolerances; very thin webs and flanges possible; machining generally not necessary; very good material utilization	High forging forces, intricate dies, and provision for removing forging from dies

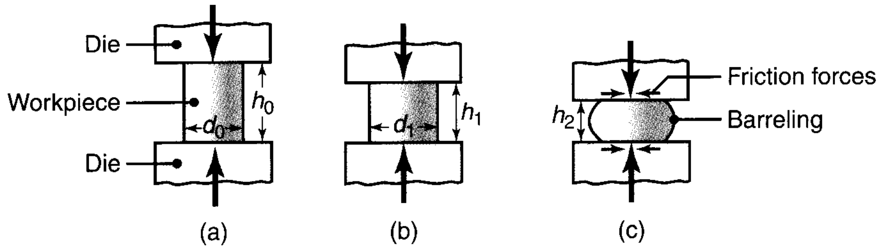


FIGURE 14.3 (a) Solid cylindrical billet upset between two flat dies. (b) Uniform deformation of the billet without friction. (c) Deformation with friction. Note barreling of the billet caused by friction forces at the billet–die interfaces.

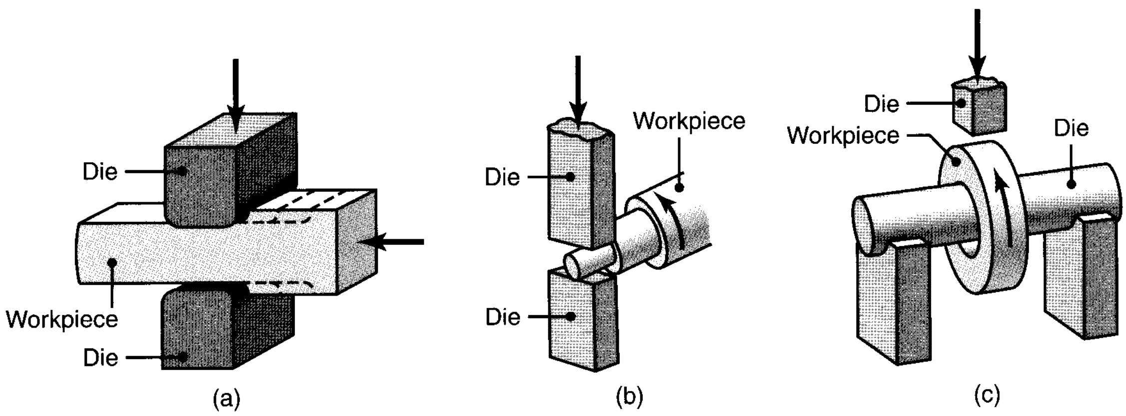


FIGURE 14.4 (a) Schematic illustration of a cogging operation on a rectangular bar. Blacksmiths use this process to reduce the thickness of bars by hammering the part on an anvil. Reduction in thickness is accompanied by barreling, as in Fig. 14.3c. (b) Reducing the diameter of a bar by open-die forging; note the movements of the dies and the workpiece. (c) The thickness of a ring being reduced by open-die forging.

lubricant. Barreling also can develop in upsetting hot workpieces between cold dies. The material at or near the die surfaces cools rapidly, while the rest of the workpiece remains relatively hot. Consequently, the material at the top and bottom of the workpiece has higher resistance to deformation than the material at the center. As a result, the central portion of the workpiece expands laterally to a greater extent than do the ends. Barreling from thermal effects can be reduced or eliminated by using heated dies. Thermal barriers, such as glass cloth, at the die–workpiece interfaces also can be used for this purpose.

Cogging (also called *drawing out*) is basically an open-die forging operation in which the thickness of a bar is reduced by successive forging steps (*bites*) at specific intervals (Fig. 14.4a). The thickness of bars and rings can be reduced by similar open-die forging techniques, as shown in Figs. 14.4b and c. Because the contact area between the die and the workpiece is small, a long section of a bar can be reduced in thickness without requiring large forces or heavy machinery. Blacksmiths perform such operations with a hammer and an anvil, using hot pieces of metal. Typical products are iron fences of various designs. Note that cogging can be a rough substitute for rolling operations. Cogging of larger workpieces usually is done using mechanized equipment and computer controls in which lateral and vertical movements are coordinated to produce the desired part.

Forging Force. The *forging force*, F, in an *open-die forging* operation on a solid cylindrical workpiece can be estimated from the formula

$$F = Y_f \pi r^2 \left(1 + \frac{2\mu r}{3h}\right), \tag{14.1}$$

where Y_f is the *flow stress* of the material (see Example 14.1), μ is the coefficient of friction between the workpiece and the die, and r and h are, respectively, the instantaneous radius and height of the workpiece. (Derivations of this formula and of others for various forging processes are given in references listed in the bibliography at the end of the chapter.)

EXAMPLE 14.1 Calculation of Forging Force in Upsetting

A solid cylindrical slug made of 304 stainless steel is 150 mm in diameter and 100 mm high. It is reduced in height by 50% at room temperature by open-die forging with flat dies. Assuming that the coefficient of friction is 0.2, calculate the forging force at the *end* of the stroke.

Solution: The forging force at the end of the stroke is calculated using Eq. (14.1), in which the dimensions pertain to the final dimensions of the forging. Thus, the final height is $h = 100/2 = 50$ mm, and the final radius, r, is determined from volume constancy by equating the volumes before and after deformation. Hence,

$$(\pi)(75)^2(100) = (\pi)(r)^2(50).$$

Therefore, $r = 106$ mm.

The quantity Y_f in Eq. (14.1) is the flow stress of the material, which is the stress required to continue plastic deformation of the workpiece at a particular true strain. The absolute value of the true strain that the workpiece has undergone at the end of the stroke in this operation is

$$\varepsilon = \ln\left(\frac{100}{50}\right) = 0.69.$$

We can determine the flow stress by referring to Eq. (2.8) and noting from Table 2.3 that, for 304 stainless steel, $K = 1275$ MPa and $n = 0.45$. Thus, for a true strain of 0.69, the flow stress is calculated to be 1100 MPa. Another method is to refer to Fig. 2.6 and note that the flow stress for 304 stainless steel at a true strain of 0.69 is about 1000 MPa. The small difference between the two values is due to the fact that the data in Table 2.3 and Fig. 2.6 are from different sources. Taking the latter value, the forging force now can be calculated, noting that in this problem the units in Eq. (14.1) must be in N and m. Thus,

$$F = (1000)(10^6)(\pi)(0.106)^2(1) + \frac{(2)(0.2)(0.106)}{(3)(0.050)}$$

$$= 4.5 \times 107 \text{ N} = 45 \text{ MN}.$$

14.3 Impression-die and Closed-die Forging

In *impression-die forging*, the workpiece takes the shape of the die cavity while being forged between two shaped dies (Figs. 14.5a through c). This process usually is carried out at elevated temperatures to lower the required forces and attain enhanced ductility in the workpiece. Note in Fig. 14.5c that, during deformation, some of the material flows outward and forms a **flash**. The flash has an important role in impression-die forging: The high pressure and the resulting high frictional resistance in the flash presents a severe constraint on any outward flow of the material in the die. Thus, based on the principle that in plastic deformation the material flows in the direction of least resistance (because it requires less energy), the material flows preferentially into the die cavity, ultimately filling it completely.

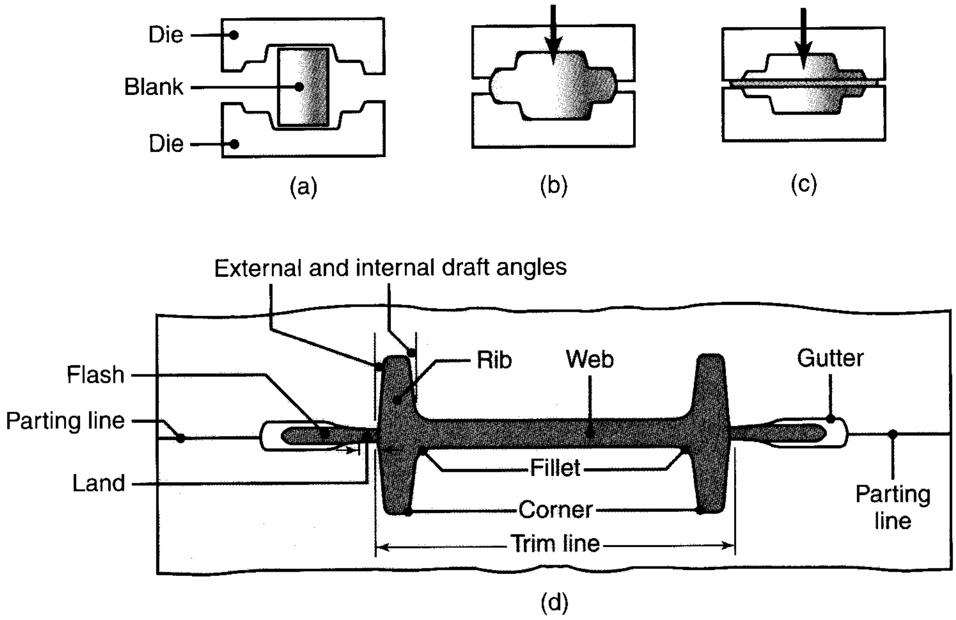


FIGURE 14.5 (a) through (c) Stages in impression-die forging of a solid round billet. Note the formation of flash, which is excess metal that is subsequently trimmed off. (d) Standard terminology for various features of a forging die.

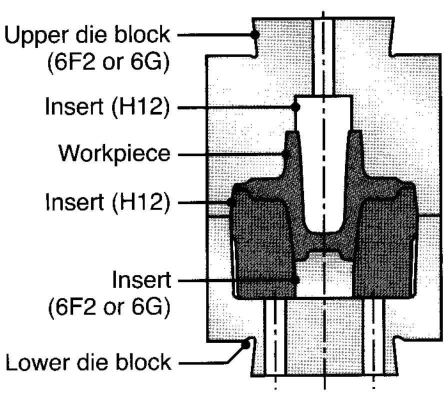


FIGURE 14.6 Die inserts used in forging an automotive axle housing. (See Section 5.7 for die materials.)

The standard terminology for a typical forging die is shown in Fig. 14.5d. Instead of being made as one piece, dies may be made of several pieces (segmented), including **die inserts** (Fig. 14.6) and particularly for complex shapes. The inserts can be replaced easily in the case of wear or failure in a particular section of the die and usually are made of stronger and harder materials.

The blank to be forged is prepared by (a) *cropping* from an extruded or drawn bar stock; (b) preforming from operations such as *powder metallurgy*; (c) *casting*; or (d) using a preformed blank from a prior forging operation. The blank is placed on the lower die, and as the upper die begins to descend, the blank's shape gradually changes—as is shown for the forging of a connecting rod in Fig. 14.7a.

Preforming operations (Figs. 14.7b and c) typically are used to distribute the material properly into various regions of the blank using simple shaped dies of various contours. In **fullering**, material is *distributed away* from an area. In **edging**, it is *gathered into* a localized area. The part then is formed into the rough shape (say, a connecting rod) by a process called **blocking**, using *blocker dies*. The final operation is the finishing of the forging in *impression dies* that give the forging its final shape. The flash is removed later by a trimming operation (Fig. 14.8).

Forging Force. The *forging force, F*, required to carry out an *impression-die forging* operation can be estimated from the formula

$$F = kY_fA, \tag{14.2}$$

where k is a multiplying factor obtained from Table 14.2, Y_f is the flow stress of the material at the forging temperature, and A is the projected area of the forging,

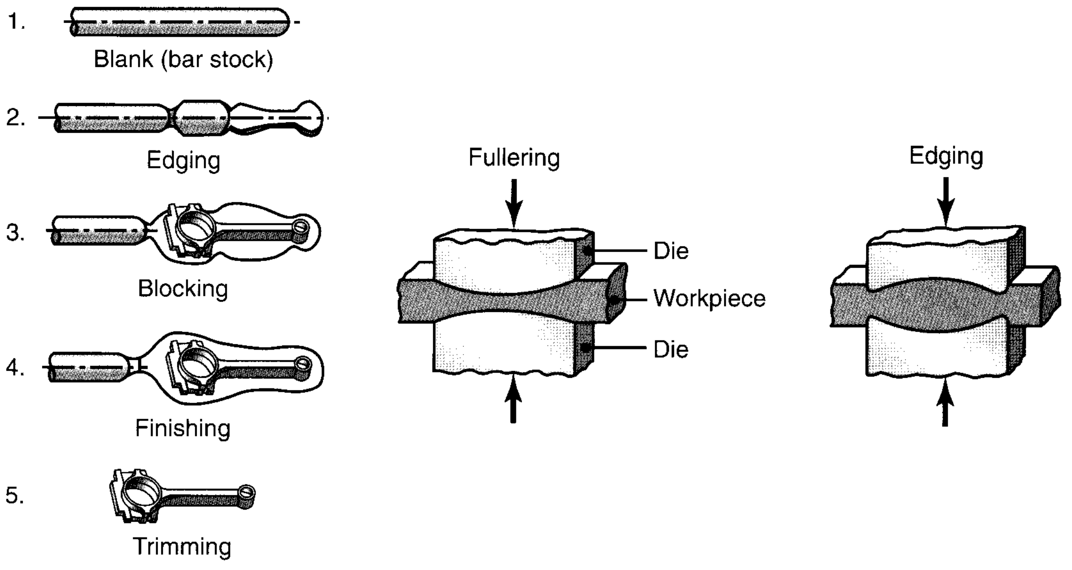


FIGURE 14.7 (a) Stages in forging a connecting rod for an internal combustion engine. Note the amount of flash required to ensure proper filling of the die cavities. (b) Fullering and (c) edging operations to distribute the material properly when preshaping the blank for forging.

including the flash. In hot-forging operations, the actual forging pressure for most metals typically ranges from 550 to 1000 MPa. As an example, assume that the flow stress of a material at the forging temperature is 700 MPa, and a part (such as that shown in Fig. 14.7a) has a projected area (with flash) of 38,000 mm^2. Taking a value of $k = 10$ from Table 14.2, the forging force would be $F = (10)(700)(38{,}000) = 266$ MN.

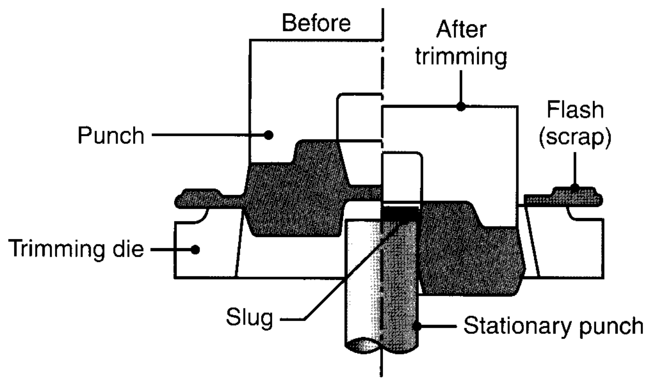


FIGURE 14.8 Trimming flash from a forged part. Note that the thin material at the center is removed by punching.

Closed-die Forging. The process shown in Fig. 14.5 also is referred to as *closed-die forging*. However, in true closed-die forging, flash does not form (hence the term *flashless forging*), and the workpiece completely fills the die cavity (see right side of Fig. 14.9b). Consequently, the forging pressure is very high, and accurate control of the blank volume and proper die design are essential to producing a forging with the desired dimensional tolerances. Undersized blanks prevent the complete filling of the die cavity; conversely, oversized blanks generate excessive pressures and may cause dies to fail prematurely or the machine to jam.

TABLE 14.2

Range of k Values for Eq. (14.2)

Shape	k
Simple shapes, without flash	3–5
Simple shapes, with flash	5–8
Complex shapes, with flash	8–12

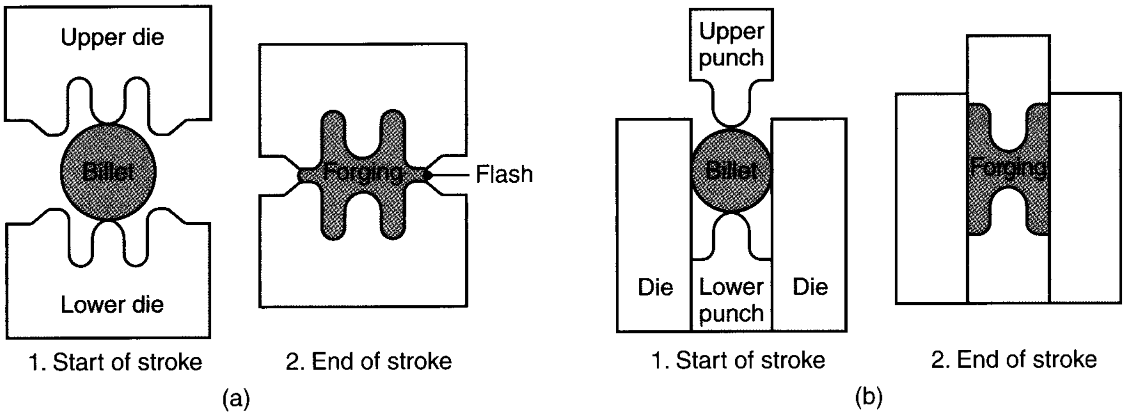


FIGURE 14.9 Comparison of (a) closed-die forging with flash and (b) precision or flashless forging of a round billet. *Source*: After H. Takemasu, V. Vazquez, B. Painter, and T. Altan.

Regardless, the term *closed-die forging* is often applied to impression die forging with flash generation, whereas *open-die forging* generally applies to operations with simple dies and tooling and with large deformations.

Precision Forging. In order to reduce the number of additional finishing operations required—hence the cost—the trend has been toward greater precision in forged products (net-shape forming). Typical precision-forged products are gears, connecting rods, and turbine blades. Precision forging requires (a) special and more complex dies, (b) precise control of the blank's volume and shape, and (c) accurate positioning of the blank in the die cavity. Also, because of the higher forces required to obtain fine details on the part, this process requires higher capacity equipment. Aluminum and magnesium alloys are particularly suitable for precision forging because of the relatively low forging loads and temperatures that they require; however, steels and titanium also can be precision forged.

Forging Practice and Product Quality. A forging operation typically involves the following sequence of steps:

1. Prepare a slug, billet, or preform by processes such as shearing (cropping), sawing, or cutting off. If necessary, clean surfaces by such means as shot blasting.
2. For hot forging, heat the workpiece in a suitable furnace and then, if necessary, descale it with a wire brush, water jet, steam, or by scraping. Some descaling also may occur during the initial stages of forging, when the scale (which is brittle) falls off during deformation.
3. For hot forging, preheat and lubricate the dies; for cold forging, lubricate the blank.
4. Forge the billet in appropriate dies and in the proper sequence. If necessary, remove any excess material (such as flash) by trimming, machining, or grinding.
5. Clean the forging, check its dimensions, and (if necessary) machine it to final dimensions and specified tolerances.
6. Perform additional operations, such as straightening and heat treating (for improved mechanical properties). Also, perform any finishing operations that may be required, such as machining and grinding.
7. Inspect the forging for any external and internal defects.

The quality, dimensional tolerances, and surface finish of a forging depend on how well these operations are performed and controlled. Generally, dimensional tolerances range between ±0.5 and ±1% of the dimensions of the forging. In good practice, tolerances for hot forging of steel are usually less than ±6 mm; in precision forging, they can be as low as ±0.25 mm. Other factors that contribute to dimensional inaccuracies are draft angles, radii, fillets, die wear, die closure (whether the dies have closed properly), and mismatching of the dies. The surface finish of the forging depends on blank preparation, die surface finish, die wear, and the effectiveness of the lubricant.

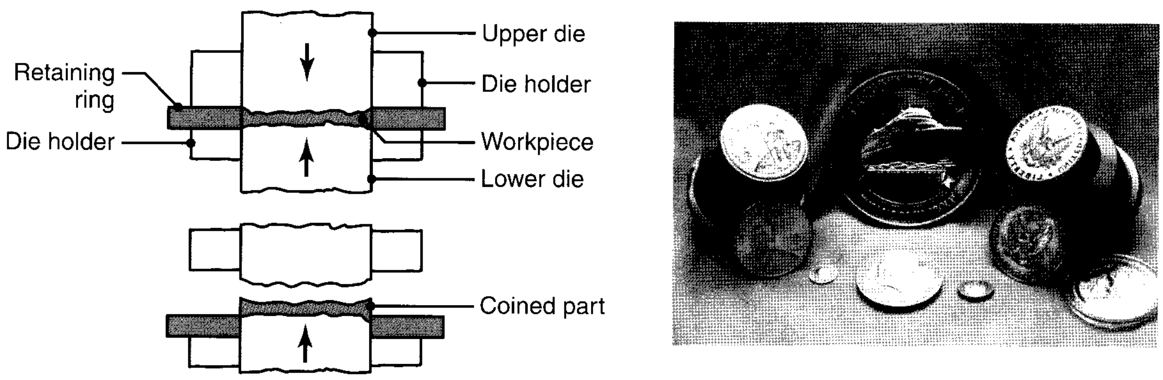
14.4 Various Forging Operations

Several other operations related to the basic forging process are carried out in order to impart the desired shape and features to forged products.

Coining. This is essentially a closed-die forging process that is typically used in the minting of coins, medallions, and jewelry (Fig. 14.10). The blank or slug is coined in a completely closed die cavity. In order to produce fine details (for example, the detail on newly minted coins), the pressures required can be as high as five or six times the strength of the material. On some parts, several coining operations may be required. Lubricants cannot be applied in coining, because they can become entrapped in the die cavities and (being incompressible) prevent the full reproduction of die-surface details and surface finish.

Marking parts with letters and numbers also can be done rapidly through coining. In addition, the process is used with forgings and other products to improve surface finish and to impart the desired dimensional accuracy with little or no change in part size. Called **sizing**, this process requires high pressures.

Heading. Also called **upset forging**, *heading* is essentially an upsetting operation, usually performed on the end of a round rod or wire in order to increase the cross section. Typical products are nails, bolt heads, screws, rivets, and various other fasteners (Fig. 14.11a). Heading can be carried out cold, warm, or hot. An important



(a) (b)

FIGURE 14.10 (a) Schematic illustration of the coining process. The earliest coins were made by open-die forging and lacked precision and sharp details. (b) An example of a modern coining operation, showing the coins and tooling. Note the detail and superior surface finish that can be achieved in this process. *Source*: Courtesy of C & W Steel Stamp Co., Inc.

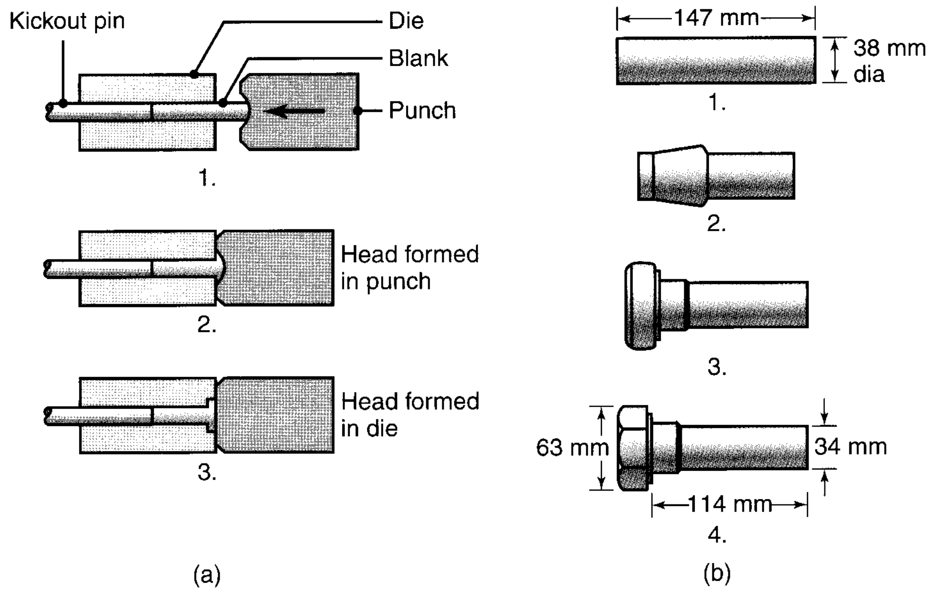


FIGURE 14.11 (a) Heading operation to form heads on fasteners, such as nails and rivets. (b) Sequence of operations used to produce a typical bolt head by heading.

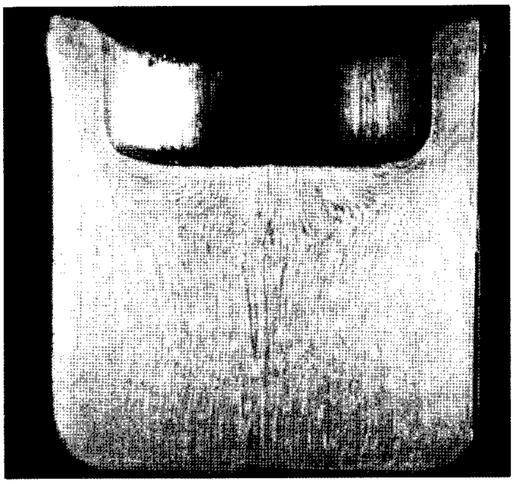


FIGURE 14.12 A pierced round billet showing grain-flow pattern. (See also Fig. 14.2c). *Source*: Courtesy of Ladish Co., Inc.

consideration in heading is the tendency for the bar to buckle if its unsupported length-to-diameter ratio is too high. This ratio usually is limited to less than 3:1, but with appropriate dies, it can be higher. For example, higher ratios can be accommodated if the diameter of the die cavity is not more than 1.5 times the bar diameter.

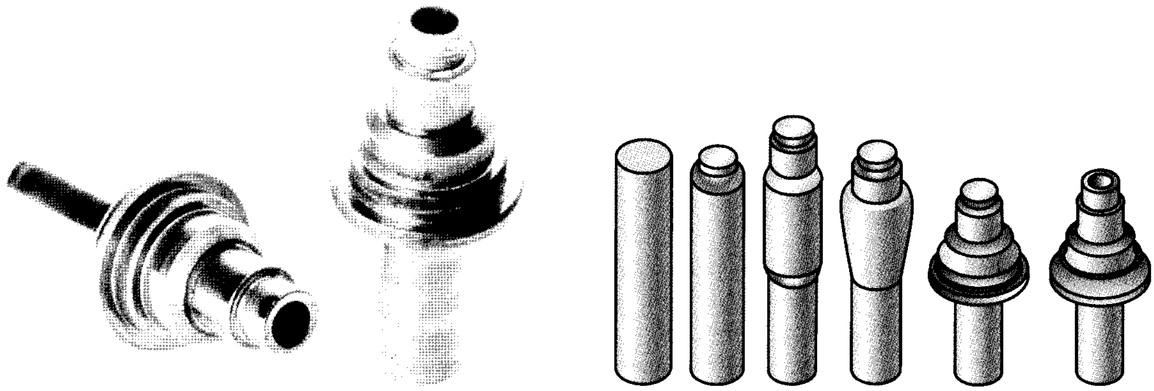
Heading operations are performed on machines called **headers**, which usually are highly automated with production rates of hundreds of pieces per minute for small parts. Hot heading operations on larger parts typically are performed on *horizontal upsetters*. These machines tend to be noisy; a soundproof enclosure or the use of ear protectors is required. Heading operations can be combined with cold-extrusion processes to make various parts, as described in Section 15.4.

Piercing. This is a process of indenting (but not breaking through) the surface of a workpiece with a punch in order to produce a cavity or an impression (Fig. 14.12). The workpiece may be confined in a container (such as a die cavity) or may be unconstrained. The deformation of the workpiece will depend on how much it is constrained from flowing freely as the punch descends. A common example of piercing is the indentation of the hexagonal cavity in bolt heads. Piercing may be followed by punching to produce a hole in the part. (For a similar depiction of this situation, see the *slug* above the stationary punch in the central portion of Fig. 14.8.) Piercing also is performed to produce hollow regions in forgings using side-acting auxiliary equipment.

The *piercing force* depends on (a) the cross-sectional area and the tip geometry of the punch, (b) the strength of the material, and (c) the magnitude of friction at the sliding interfaces. The pressure may range from three to five times the strength of the material, which is approximately the same level of stress required to make an indentation in hardness testing (Section 2.6).

CASE STUDY 14.1 Manufacture of a Stepped Pin by Heading and Piercing Operations

Fig. 14.13a shows a stepped pin made from SAE 1008 steel and used as a part of a roller assembly to adjust the position of a car seat. The part is fairly complex and must be produced in a progressive manner in order to produce the required details and fill the die completely. The cold-forging steps used to produce this part are shown in Fig. 14.13b. First, a solid, cylindrical blank is extruded in two operations, followed by an upsetting operation. The upsetting operation uses a conical cross section in the die to produce the preform and is oriented such that material is concentrated at the top of the part in order to ensure proper die filling. After the impression-die forming, a piercing operation is performed to forms the bore. The part is made to net shape on a cold-forming machine at a rate of 240 parts per minute.



(a) (b)

FIGURE 14.13 (a) The stepped pin used in Case Study 14.1. (b) Illustration of the manufacturing steps used to produce the stepped pin. *Source*: Courtesy of National Machinery, LLC.

Hubbing. This process consists of pressing a hardened punch with a particular tip geometry into the surface of a block of metal. The cavity produced is subsequently used as a die for forming operations, such as those employed in the making of tableware. The die cavity usually is shallow, but for deeper cavities, some material may be removed from the surface by machining prior to hubbing (see Figs. 24.2c and d). The *hubbing force* can be estimated from the equation

$$\text{Hubbing force} = 3(\text{UTS})(A), \tag{14.3}$$

where UTS is obtained from Table 2.2 and A is the projected area of the impression. For example, for high-strength steel with UTS = 1500 MPa and a part with a projected area of 400 mm^2, the hubbing force is (3)(1500 N/mm^2)(400 mm^2) = 1.8 MN.

Orbital Forging. In this process, the upper die moves along an orbital path and forms the part *incrementally*. The operation is similar to the action of a mortar and pestle used for crushing herbs and seeds. Although not in common use, typical components that may be forged by this process are disk-shaped and conical parts, such as bevel gears and gear blanks. The forging force is relatively small, because at any particular instant, the die contact is concentrated onto a small area of the workpiece (see also *incremental forging* below). The operation is relatively quiet, and parts can be formed within 10 to 20 cycles of the orbiting die.

Incremental Forging. In this process, a tool forges a blank into a shape in several small steps. The operation is somewhat similar to cogging (see Fig. 14.4a), in which the die penetrates the blank to different depths along the surface. Because of the smaller area of contact with the die, the process requires much lower forces compared with conventional impression-die forging, and the tools are simpler and less costly.

Isothermal Forging. Also known as **hot-die forging**, this process heats the dies to the same temperature as that of the hot workpiece. Because the workpiece remains hot, its flow strength and high ductility are maintained during forging. Also, the forging load is low, and material flow within the die cavity is improved. Complex parts with good dimensional accuracy can be isothermally forged to near-net shape by one stroke in a hydraulic press. The dies for hot forging of high-temperature alloys usually are made of nickel or molybdenum alloys (because of their resistance to high temperature), but steel dies can be used for aluminum alloys. Isothermal forging is expensive and the production rate is low. However, it can be economical for specialized, intricate forgings made of materials such as aluminum, titanium, and superalloys, provided that the quantity required is sufficiently high to justify the die costs.

Rotary Swaging. In this process (also known as *radial forging, rotary forging*, or simply *swaging*), a solid rod or tube is subjected to radial impact forces by a set of reciprocating dies of the machine (Figs. 14.14a and b). The die movements are obtained by means of a set of rollers in a cage in an action similar to that of a roller bearing. The workpiece is stationary and the dies rotate (while moving radially in their slots), striking the workpiece at rates as high as 20 strokes per second. In *die-closing swaging machines*, die movements are obtained through the reciprocating motion of wedges (Fig. 14.14c). The dies can be opened wider than those in rotary swagers, thereby accommodating large-diameter or variable-diameter parts. In another type of machine, the dies do not rotate, but move radially in and out. Typical products made are screwdriver blades and soldering-iron tips.

Swaging also can be used to *assemble* fittings over cables and wire; in such cases, the tubular fitting is swaged directly onto the cable. The process is also used for operations such as *pointing* (tapering the tip of a cylindrical part) and *sizing* (finalizing the dimensions of a part).

Swaging generally is limited to a maximum workpiece diameter of about 150 mm; parts as small as 0.5 mm have been swaged. Dimensional tolerances range from ± 0.05 to ± 0.5 mm. The process is suitable for medium-to-high rates of production, with rates as high as 50 parts per minute possible, depending on part complexity. Swaging is a versatile process and is limited in length only by the length of the bar supporting the mandrel (if one is needed).

Tube Swaging. In this process, the internal diameter and/or the thickness of the tube is reduced with or without the use of *internal mandrels* (Figs. 14.15a and b). For small-diameter tubing, high-strength wire can be used as a mandrel. Mandrels also can be made with longitudinal grooves, to allow swaging of internally shaped tubes (Fig. 14.15c). For example, the rifling in gun barrels (internal spiral grooves to give gyroscopic effect to bullets) can be produced by swaging a tube over a mandrel with spiral grooves. Special machinery has been built to swage gun barrels and other parts with starting diameters as large as 350 mm.

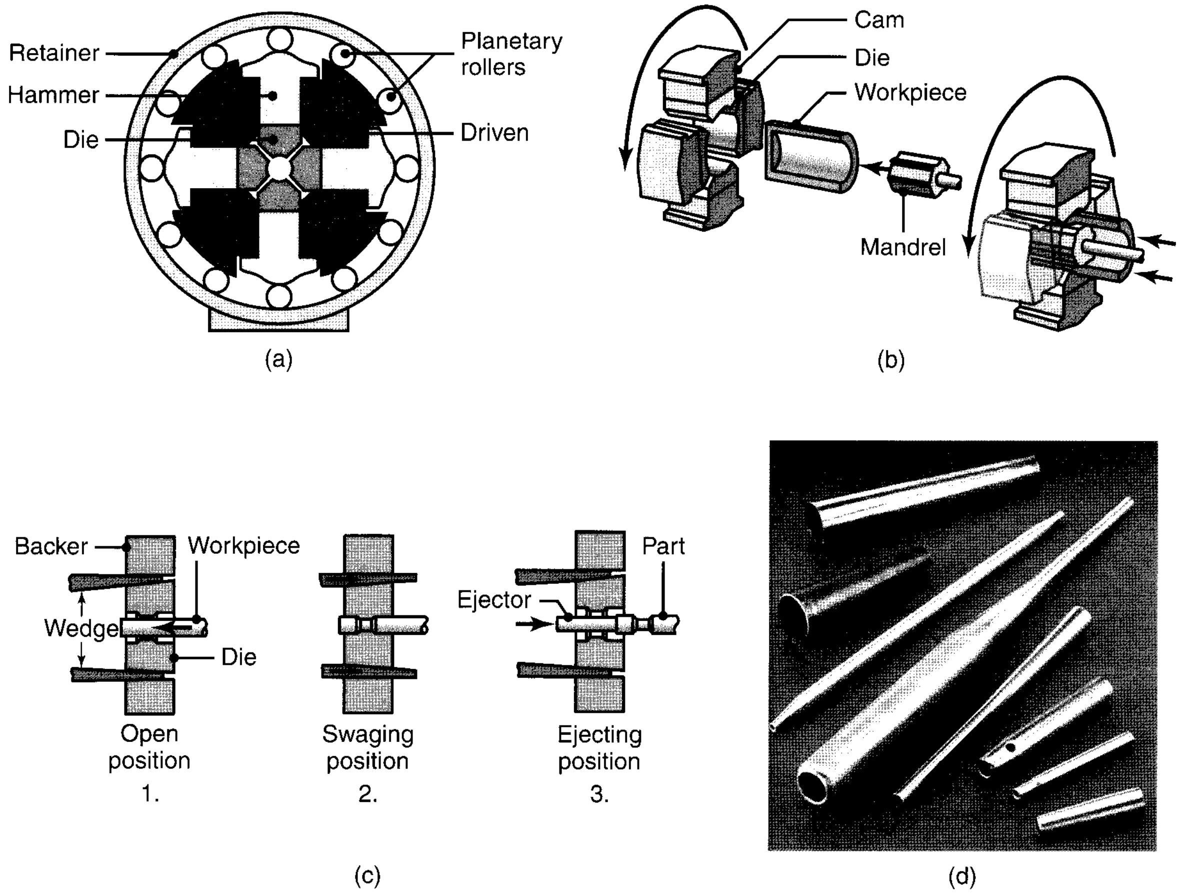


FIGURE 14.14 (a) Schematic illustration of the rotary-swaging process. (b) Forming internal profiles on a tubular workpiece by swaging. (c) A die-closing swaging machine, showing forming of a stepped shaft. (d) Typical parts made by swaging. *Source*: (d) Courtesy of J. Richard Industries.

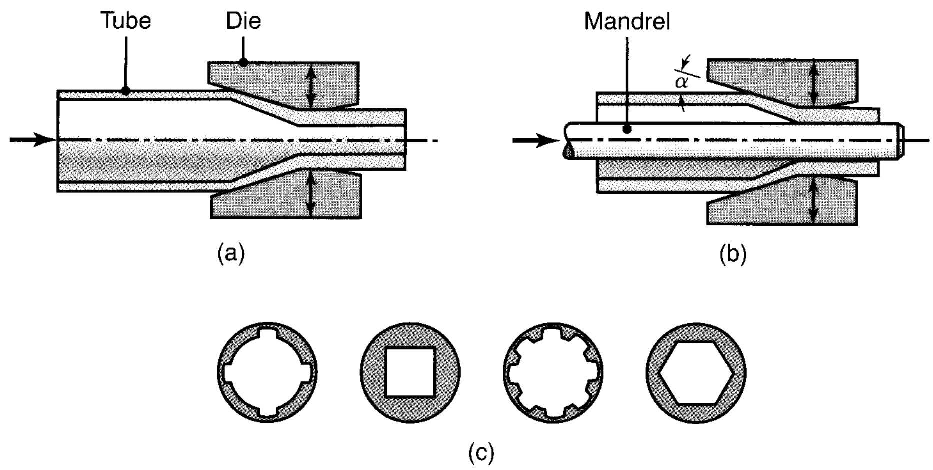


FIGURE 14.15 (a) Swaging of tubes without a mandrel; note the increase in wall thickness in the die gap. (b) Swaging with a mandrel; note that the final wall thickness of the tube depends on the mandrel diameter. (c) Examples of cross sections of tubes produced by swaging on shaped mandrels. Rifling (internal spiral grooves) in small gun barrels can be made by this process.

14.5 Forgeability of Metals; Forging Defects

Forgeability is generally defined as the capability of a material to undergo deformation without cracking. Various tests have been developed to quantify forgeability; however, because of their complex nature, only two simple tests have had general acceptance: upsetting and hot twist.

In the **upsetting test**, a solid, cylindrical specimen is upset between flat dies, and the reduction in height at which cracking on the barreled surfaces begins is noted (see also Fig. 2.20d). The greater the deformation prior to cracking, the greater the forgeability of the metal. The second method is the **hot-twist test**, in which a round specimen is twisted continuously in the same direction until it fails. This test is performed on a number of specimens and at different temperatures, and the number of complete turns that each specimen undergoes before failure at each temperature is plotted. The temperature at which the maximum number of turns occurs then becomes the forging temperature for maximum forgeability. The hot-twist test has been found to be useful particularly for steels.

The forgeability of various metals and alloys is given in Table 14.3 in decreasing order. Forgeability is based on considerations such as ductility and strength of the material, forging temperature required, frictional behavior, and the quality of the forgings produced. These ratings should be regarded only as general guidelines. Typical *hot-forging temperature* ranges for various metals and alloys are included in Table 14.3. Note that higher forging temperature does not necessarily indicate greater difficulty in forging that material. For *warm* forging, temperatures range from 200° to 300°C for aluminum alloys and from 550° to 750°C for steels.

Forging Defects. In addition to surface cracking, other defects can develop during forging as a result of the material flow pattern in the die, as described next in Section 14.6 regarding die design. For example, if there is an insufficient volume of material to fill the die cavity completely, the web may buckle during forging and develop laps (Fig. 14.16a). On the other hand, if the web is too thick, the excess material flows past the already formed portions of the forging and develops internal cracks (Fig. 14.16b).

TABLE 14.3

Forgeability of Metals, in Decreasing Order

Metal or alloy	Approximate range of hot-forging temperatures (°C)
Aluminum alloys	400–550
Magnesium alloys	250–350
Copper alloys	600–900
Carbon- and low-alloy steels	850–1150
Martensitic stainless steels	1100–1250
Austenitic stainless steels	1100–1250
Titanium alloys	700–950
Iron-based superalloys	1050–1180
Cobalt-based superalloys	1180–1250
Tantalum alloys	1050–1350
Molybdenum alloys	1150–1350
Nickel-based superalloys	1050–1200
Tungsten alloys	1200–1300

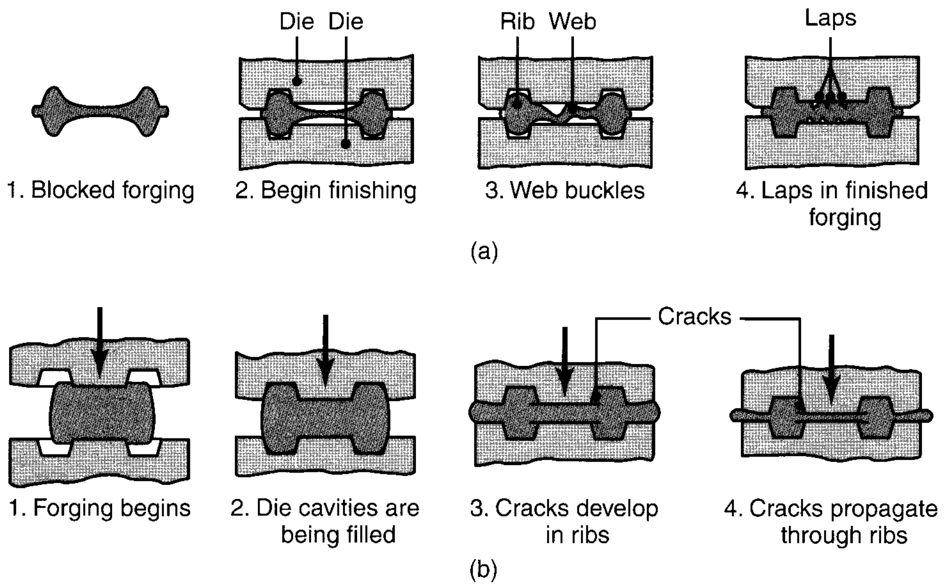


FIGURE 14.16 Examples of defects in forged parts. (a) Laps formed by web buckling during forging; web thickness should be increased to avoid this problem. (b) Internal defects caused by an oversized billet. Die cavities are filled prematurely, and the material at the center flows past the filled regions as the dies close.

The various radii in the forging-die cavity can significantly influence the formation of such defects. Internal defects also may develop from (a) nonuniform deformation of the material in the die cavity, (b) temperature gradients throughout the workpiece during forging, and (c) microstructural changes caused by phase transformations. The grain-flow pattern of the material in forging also is important. The flow lines may reach a surface perpendicularly, as shown in Fig. 14.12. In this condition, known as **end grains**, the grain boundaries become exposed directly to the environment and can be attacked by it, developing a rough surface and also acting as stress raisers.

Forging defects can cause fatigue failures, and they also may lead to such problems as corrosion and wear during the service life of the forged component. The importance of inspecting forgings prior to their placement in service, particularly in critical applications, such as aircraft, is obvious. Inspection techniques for manufactured parts are described in Chapter 36.

14.6 Die Design, Die Materials, and Lubrication

The design of forging dies requires considerable knowledge and experience regarding the shape and complexity of the workpiece, its ductility, its strength and sensitivity to deformation rate and temperature, and its frictional characteristics. Die distortion under high forging loads is also an important design consideration, particularly if close dimensional tolerances are required. The most important rule in die design is the fact that the part will flow in the direction of least resistance. Thus, the workpiece *intermediate shapes* should be planned so that they properly fill the die cavities. An example of the intermediate shapes for a connecting rod is given in Fig. 14.7a.

With continuing advances in developing reliable simulation of all types of metalworking operations, software is available to help predict material flow in forging-die cavities. The simulation incorporates various conditions, such as workpiece temperature and heat transfer, to tooling, frictional conditions at die–workpiece contact surfaces, and forging speed. Such software can be very helpful in die design and in eliminating future problems with defective forgings (see also Section 38.7).

Preshaping. In a properly preshaped workpiece, the material should not flow easily into the flash (otherwise die filling will be incomplete), the grain flow pattern should be favorable for the products' strength and reliability, and sliding at the workpiece–die interfaces should be minimized in order to reduce die wear. The selection of preshapes requires considerable experience and involves calculations of cross-sectional areas at each location in the forging. Computer modeling and simulation techniques are useful in such calculations.

Die Design Features. The terminology for forging dies is shown in Fig. 14.5d, and the significance of various features is described next. Some of these considerations are similar to those for casting (Section 12.2). For most forgings, the **parting line** is located at the largest cross section of the part. For simple symmetrical shapes, the parting line is normally a straight line at the center of the forging, but for more complex shapes, the line may not lie in a single plane. The dies are then designed in such a way that they lock during engagement, in order to avoid side thrust, balance forces, and maintain die alignment during forging.

After sufficiently constraining lateral flow to ensure proper die filling, the flash material is allowed to flow into a *gutter*, so that the extra flash does not increase the forging load excessively. A general guideline for flash thickness is 3% of the maximum thickness of the forging. The length of the *land* is usually two to five times the flash thickness.

Draft angles are necessary in almost all forging dies in order to facilitate removal of the part from the die. Upon cooling, the forging shrinks both radially and longitudinally, so internal draft angles (about 7° to 10°) are made larger than external ones (about 3° to 5°).

Selection of the proper radii for corners and fillets is important in ensuring smooth flow of the metal into the die cavity and improving die life. Small radii generally are undesirable because of their adverse effect on metal flow and their tendency to wear rapidly (as a result of stress concentration and thermal cycling). Small fillet radii also can cause fatigue cracking of the dies. As a general rule, these radii should be as large as can be permitted by the design of the forging. As with the patterns used in casting, *allowances* are provided in forging-die design when machining the forging is necessary to obtain final desired dimensions and surface finish. Machining allowance should be provided at flanges, at holes, and at mating surfaces.

Die Materials. Most forging operations (particularly for large parts) are carried out at elevated temperatures. General requirements for die materials therefore are

- Strength and toughness at elevated temperatures
- Hardenability and ability to harden uniformly
- Resistance to mechanical and thermal shock
- Wear resistance, particularly resistance to abrasive wear, because of the presence of scale in hot forging.

Common die materials are tool and die steels containing chromium, nickel, molybdenum, and vanadium (see Tables 5.7 and 5.8). Dies are made from die blocks, which themselves are forged from castings and then machined and finished to the desired shape and surface finish. Die-manufacturing methods are described in Section 14.7.

Lubrication. A wide variety of metalworking fluids can be used in forging, as described in Section 33.7. Lubricants greatly influence friction and wear. Consequently, they affect the forces required [see Eq. (14.1)], die life, and the manner in which the material flows into the die cavities. Lubricants can also act as a thermal barrier between the hot workpiece and the relatively cool dies—thus slowing the rate of cooling of the workpiece and improving metal flow. Another important role of the lubricant is to act as a *parting agent*, preventing the forging from sticking to the dies and helping release it from the die.

14.7 Die-manufacturing Methods and Die Failures

From the topics described thus far, it should be evident that dies, their quality, and die life are highly significant aspects of the total manufacturing operation, including the quality of the parts produced. This is particularly noteworthy in view of the fact that the vast majority of discrete parts that are produced in large quantities (such as gears, shafts, bolts, etc.), as well as castings of all types of products, are made in individual dies and molds. Dies also have an impact on the overall economics of manufacturing, because of their cost and the lead time needed to produce them, as some dies require months to manufacture. Equally important considerations are the maintenance of dies and their modifications as parts are first produced.

Several manufacturing methods, either singly or in combination, can be used to make dies for forging, as well as for other metalworking processes. These methods include casting, forging, machining, grinding, electrical and electrochemical methods—particularly electrical-discharge machining (EDM) and wire EDM—and the use of lasers for small dies. An important and continuing development is the production of tools and dies by **rapid tooling** using rapid protoyping techniques, described in Section 20.5.

The process of producing a die cavity in a **die block** is called **die sinking**. The process of *hubbing* (Section 14.4), either cold or hot, also may be used to make small dies with shallow cavities. Dies are usually heat treated for higher hardness and wear resistance (Chapter 33). If necessary, their surface profile and finish are improved further by finish grinding and polishing, either by hand or by programmable industrial robots.

The choice of a die-manufacturing method depends on its size and shape and the particular operation in which the die is to be used, such as casting, forging, extrusion, powder metallurgy, or plastics molding. As in all manufacturing operations, cost often dictates the process selected, because tool and die costs can be significant in manufacturing operations. Dies of various sizes and shapes can be **cast** from steels, cast irons, and nonferrous alloys. The processes used for preparing them may range from sand casting (for large dies weighing several tons) to shell molding (for casting small dies). Cast steels generally are preferred for large dies because of their strength and toughness, as well as the ease with which the steel composition, grain size, and other properties can be controlled and modified.

Most commonly, dies are *machined* from *forged die blocks* by processes such as high-speed milling, turning, grinding, and electrical discharge and electrochemical machining. Such an operation is shown in Fig. I.11b for making molds for eyeglass frames. For high-strength and wear-resistant die materials that are hard or are heat treated (and thus difficult to machine), processes such as hard machining (Section 25.6) and electrical and elctrochemical machining are a common practice. Typically, a die is machined by milling on computer-controlled machine tools with various software packages (see Fig. I.11) that have the capability (economically) of optimizing the cutting-tool path. Thus, the best surface finish can be obtained in the least possible machining time. Equally important is the setup for machining, because dies should be machined as much as possible in one setup without having to remove them from their fixtures and reorient them for subsequent machining operations.

After heat treating to achieve the desired mechanical properties, dies usually are subjected to *finishing operations* (Section 26.7), such as grinding, polishing, and chemical and electrical processes, to obtain the desired surface finish and dimensional accuracy. This also may include *laser surface treatments* and *coatings* (Chapter 34) to improve die life. Lasers are sometimes used for die repair and reconfiguration of the worn regions of dies (see also Fig. 33.11).

Die Costs. From the preceding discussion, it is evident that the cost of a die depends greatly on its size, shape complexity, application, and surface finish required, as well as the die material and manufacturing, heat treating, and finishing methods employed. Consequently, specific die costs cannot be categorized easily. Some qualitative ranges of tool and die costs are given throughout this book, such as in Table 12.6. Even small and relatively simple dies can cost hundreds of dollars to make, and the cost of a set of dies for automotive body panels can be as much as $2 million. On the other hand, because a large number of parts usually are made from one set of dies, the *die cost per piece made* is generally a small portion of a part's manufacturing cost (see also Section 40.9). The lead time required to produce dies also can have a significant impact on the overall manufacturing cost, particularly in a global and competitive marketplace.

Die Failures. Failure of dies in manufacturing operations generally results from one or more of the following causes:

- Improper die design
- Defective or improper selection of die material
- Improper manufacturing and improper heat-treatment and finishing operations
- Overheating and heat checking (i.e., cracking caused by temperature cycling)
- Excessive wear
- Overloading (i.e., excessive force on the die)
- Improper alignment of the die components with respect to their movements
- Misuse
- Improper handling of the die.

Although these factors typically apply to dies made of tool and die steels, many also apply to other die materials, such as carbides, ceramics, and diamond.

The proper design of dies is as important as the proper selection of die materials. In order to withstand the forces involved, a die must have sufficiently large cross sections and clearances (to prevent jamming). Abrupt changes in cross section, sharp corners, radii, fillets, and a coarse surface finish (including grinding marks and their orientation on die surfaces) act as stress raisers and thus can have detrimental effects on die life. For improved strength and to reduce the tendency for cracking, dies may be made in segments and assembled into a complete die with rings that prestress the dies. Proper handling, installation, assembly, and alignment of dies are essential. Overloading of tools and dies can cause premature failure.

A common cause of failure in cold-extrusion dies is that of the operator (or of a programmable robot) to fail to remove a formed part from the die before loading it with another blank.

14.8 Forging Machines

A variety of forging machines is available with a range of capacities (tonnage), speeds, and speed–stroke characteristics (Table 14.4).

Hydraulic Presses. These presses operate at constant speeds and are *load limited*, or load restricted. In other words, a press stops if the load required exceeds its capacity. Large amounts of energy can be transmitted to a workpiece by a constant load throughout a stroke—the speed of which can be controlled. Because forging in a hydraulic press takes longer than in the other types of forging machines described next, the workpiece may cool rapidly unless the dies are heated (see *isothermal forging*, Section 14.4). Compared with mechanical presses, hydraulic presses are slower and involve higher initial costs, but they require less maintenance.

A hydraulic press typically consists of a frame with two or four columns, pistons, cylinders (Fig. 14.17), rams, and hydraulic pumps driven by electric motors. The ram speed can be varied during the stroke. Press capacities range up to 125 MN for open-die forging and up to 450 MN in North America, 640 MN in France, and 730 MN in Russia for closed-die forging. The main landing-gear support beam for the Boeing 747 aircraft is forged in a 450-MN hydraulic press, shown in Fig. 14.1c

TABLE 14.4

Typical Speed Ranges of Forging Equipment

Equipment	m/s
Hydraulic press	0.06–0.30
Mechanical press	0.06–1.5
Screw press	0.6–1.2
Gravity drop hammer	3.6–4.8
Power drop hammer	3.0–9.0
Counterblow hammer	4.5–9.0

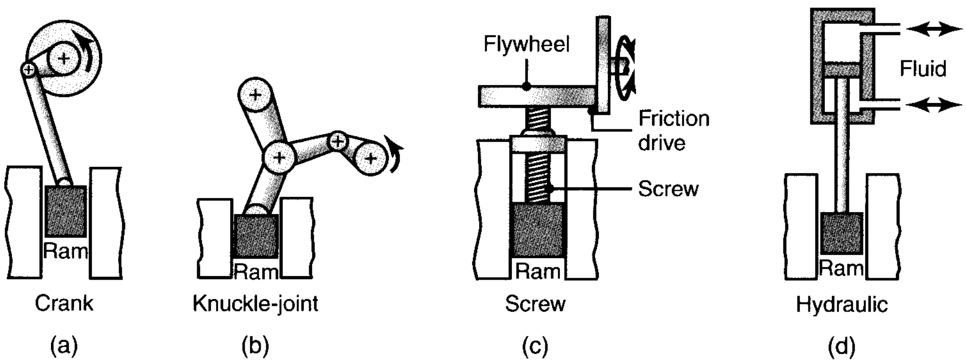


FIGURE 14.17 Schematic illustration of the principles of various forging machines. (a) Mechanical press with an eccentric drive; the eccentric shaft can be replaced by a crankshaft to give up-and-down motion to the ram. (b) Knuckle-joint press. (c) Screw press. (d) Hydraulic press.

with the part in the forefront. This part is made of a titanium alloy and weighs approximately 1350 kg.

Mechanical Presses. These presses are basically of either the crank or the eccentric type (Fig. 14.17a). The speed varies from a maximum at the center of the stroke to zero at the bottom of the stroke; thus, mechanical presses are *stroke limited.* The energy in a mechanical press is generated by a large flywheel powered by an electric motor. A clutch engages the flywheel to an eccentric shaft. A connecting rod translates the rotary motion into a reciprocating linear motion. A *knuckle-joint* mechanical press is shown in Fig. 14.17b. Because of the linkage design, very high forces can be applied in this type of press (see also Fig. 11.20).

The force available in a mechanical press depends on the stroke position and becomes extremely high at the end of the stroke. Thus, proper setup is essential to avoid breaking the dies or equipment components. Mechanical presses have high production rates, are easier to automate, and require less operator skill than do other types of machines. Press capacities generally range from 2.7 to 107 MN. Mechanical presses are preferred for forging parts with high precision.

Screw Presses. These presses (Fig. 14.17c) derive their energy from a flywheel; hence, they are *energy limited.* The forging load is transmitted through a large vertical screw, and the ram comes to a stop when the flywheel energy is dissipated. If the dies do not close at the end of the cycle, the operation is repeated until the forging is completed. Screw presses are used for various open-die and closed-die forging operations. They are suitable particularly for small production quantities, especially thin parts with high precision, such as turbine blades. Press capacities range from 1.4 to 280 MN.

Hammers. Hammers derive their energy from the potential energy of the ram, which is converted into kinetic energy; hence, they are *energy limited.* Unlike hydraulic presses, hammers (as the name implies) operate at high speeds, and the resulting low forming time minimizes the cooling of a hot forging. Low cooling rates then allow the forging of complex shapes, particularly those with thin and deep recesses. To complete the forging, several successive blows usually are made in the same die. Hammers are available in a variety of designs and are the most versatile and the least expensive type of forging equipment.

Drop Hammers. In *power drop hammers*, the ram's downstroke is accelerated by steam, air, or hydraulic pressure at about 750 kPa. Ram weights range from 225 to 22,500 kg, with energy capacities reaching 1150 kJ. In the operation of *gravity drop hammers* (a process called **drop forging**), the energy is derived from the free-falling ram. The available energy of a drop hammer is the product of the ram's weight and the height of its drop. Ram weights range from 180 to 4500 kg, with energy capacities ranging up to 120 kJ.

Counterblow Hammers. These hammers have two rams that simultaneously approach each other horizontally or vertically to forge the part. As in open-die forging operations, the part may be rotated between blows for proper shaping of the workpiece during forging. Counterblow hammers operate at high speeds and transmit less vibration to their bases. Capacities range up to 1200 kJ.

High-energy-rate Forging Machines. In these machines, the ram is accelerated rapidly by inert gas at high pressure and the part is forged in one blow at a very high speed. Although there are several types of these machines, various problems associated with their operation and maintenance, as well as die breakage and safety considerations, have greatly limited their use in industry.

14.9 Economics of Forging

Several factors are involved in the cost of forgings. Depending on the complexity of the forging, tool and die costs range from moderate to high. However, as in other manufacturing operations, these costs are spread out over the number of parts forged with that particular die set. Thus, even though the cost of workpiece material per piece made is constant, setup and tooling costs per piece decrease as the number of pieces forged increases (Fig. 14.18).

The ratio of the cost of the die material to the total cost of forging the part increases with the weight of forgings: The more expensive the material, the higher the cost of the material relative to the total cost. Because dies must be made and forging operations must be performed regardless of the size of the forging, the cost of dies and of the forging operation relative to material cost is high for small parts. By contrast, die material costs are relatively low.

The size of forgings also has some effect on cost. Sizes range from small forgings (such as utensils and small automotive components) to large ones (such as gears, crankshafts, and connecting rods for large engines). As forging size increases, the share of material cost in the total cost also increases, but at a lower rate. This occurs because (a) the incremental increase in die cost for larger dies is relatively small, (b) the machinery and operations involved are essentially the same regardless of forging size, and (c) the labor involved per piece made is not that much higher.

The total cost involved in a forging operation is not influenced to any major extent by the type of materials forged. Because they have been reduced significantly by automated and computer-controlled operations, labor costs in forging generally are moderate. Also, die design and manufacturing are now performed by computer-aided design and manufacturing techniques (Chapter 38), which result in major savings in time and effort.

The cost of forging a part compared to that of making it by various casting techniques, powder metallurgy, machining, or other methods is an important consideration in a competitive global marketplace. For example, all other factors being the same, and depending on the number of pieces required, manufacturing a certain part by, say, expendable-mold casting may well be more economical than producing it by forging for shorter production runs (Fig. 14.19). This casting method does not require expensive molds and tooling, whereas forging requires expensive dies. Some competitive aspects of manufacturing and process selection are discussed in greater detail in Chapter 40.

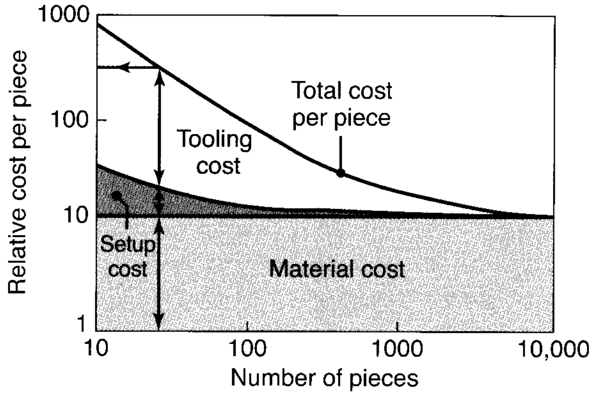


FIGURE 14.18 Typical cost per piece in forging; note how the setup and the tooling costs per piece decrease as the number of pieces forged increases if all pieces use the same die.

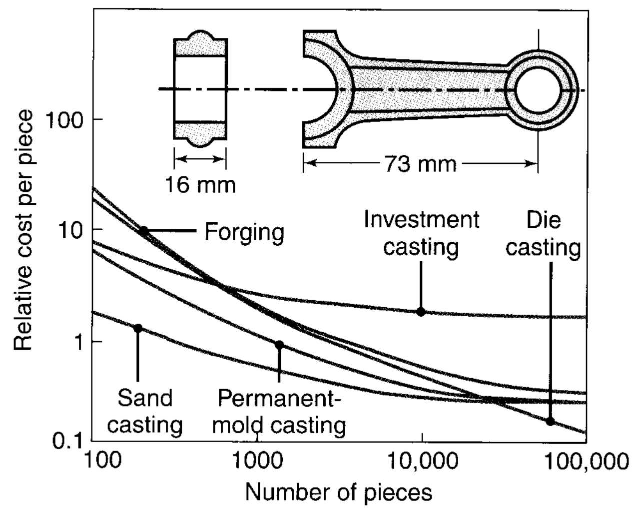


FIGURE 14.19 Relative unit costs of a small connecting rod made by various forging and casting processes. Note that, for large quantities, forging is more economical. Sand casting is the most economical process for fewer than about 20,000 pieces.

CASE STUDY 14.2 Suspension Components for the Lotus Elise Automobile

The automotive industry increasingly has been subjected to a demanding set of performance, cost, fuel efficiency, and environmental regulations. One of the main strategies in improving vehicle design with respect to all of these possibly conflicting constraints is to reduce vehicle weight while using advanced materials and manufacturing processes to preserve performance and safety. Previous design optimization has shown that weight savings of up to 34% can be realized on suspension system components—a significant savings, since suspensions make up approximately 12% of a car's mass. These weight savings could be achieved largely by developing optimum designs, utilizing advanced analytical tools, and using net-shape or near-net-shape steel forgings instead of cast-iron components. In addition, significant cost savings have been demonstrated in many parts when optimized steel forgings are used, as opposed to aluminum castings and extrusions.

The Lotus Elise is a high-performance sports car designed for superior ride and superior handling. The Lotus group investigated the use of steel forgings instead of extruded-aluminum suspension uprights in order to reduce cost and improve reliability and performance. Their development efforts consisted of two phases, shown in Fig. 14.20. The first phase involved the development of a forged-steel component that can be used on the existing Elise sports car; the second phase involved the production of a suspension upright for a new model.

A new design was developed using an iterative process with advanced software tools to reduce the number of components and to determine the optimum geometry. The material selected for the upright was an air-cooled forged steel, which gives uniform grain size and microstructure and uniform high strength without the need for heat treatment. These materials also have approximately 20% higher fatigue strengths than traditional carbon steels, such as AISI 1548-HT, which is used for similar applications.

The revised designs are summarized in Table 14.5. As can be seen, the optimized new forging

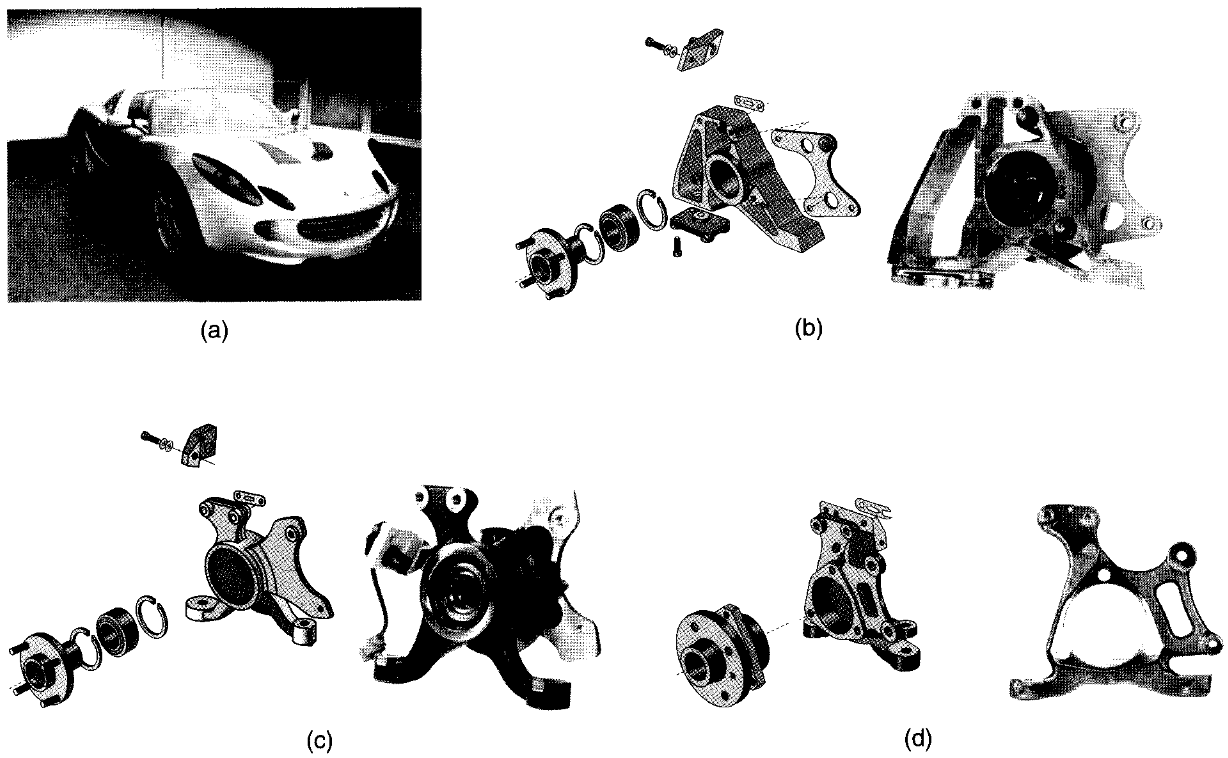


FIGURE 14.20 (a) The Lotus Elise Series 2 automobile. (b) illustration of the original design for the vertical suspension uprights, using an aluminum extrusion. (c) retrofit design, using a steel forging. (d) optimized steel forging design for new car models. *Source*: (a) Courtesy of Fox Valley Motorcars. (b) through (d) Courtesy of Lotus Engineering and the American Iron and Steel Institute.

TABLE 14.5

Comparison of Suspension Upright Designs for the Lotus Elise Automobile

Fig. 14.20 sketch	Material	Application	Mass (kg)	Cost ($)
(b)	Aluminum extrusion, steel bracket, steel bushing, housing	Original design	2.105	85
(c)	Forged steel	Phase I	2.685 (+28%)	27.7 (−67%)
(d)	Forged steel	Phase II	2.493 (+18%)	30.8 (−64%)

design (Fig. 14.20d) resulted in significant cost savings. Although it also resulted in a small weight increase when compared to the aluminum-extrusion design, the weight penalty is recognized as quite small, and the use of forged steel for such components is especially advantageous in fatigue-loading conditions constantly encountered by suspension components. The new design also had certain performance advantages in that the component stiffness is now higher, which registered as improved customer satisfaction and better "feel" during driving. Furthermore, the new design reduced the number of parts required, thus satisfying another fundamental principle in design.

Source: Courtesy of Lotus Engineering and the American Iron and Steel Institute.

SUMMARY

- Forging denotes a family of metalworking processes in which deformation of the workpiece is carried out by compressive forces applied through a set of dies. Forging is capable of producing a wide variety of structural parts with favorable characteristics, such as higher strength, improved toughness, dimensional accuracy, and reliability in service.
- The forging process can be carried out at room, warm, or high temperatures. Workpiece material behavior during deformation, friction, heat transfer, and material-flow characteristics in the die cavity are important considerations, as are the proper selection of die materials, lubricants, workpiece and die temperatures, forging speeds, and equipment.
- Various defects can develop if the forging process is not designed or controlled properly. Defects appear especially in workpiece quality, billet or preform shape, and die geometry. Computer-aided design and manufacturing techniques are now used extensively in die design and manufacturing, preform design, predicting material flow, and avoiding the possibility of internal and external defects during forging.
- A variety of forging machines is available, each with its own capabilities and characteristics. Forging operations are now highly automated and use industrial robots and computer controls.
- Swaging is a type of rotary forging in which a solid rod or a tube is reduced in diameter by the reciprocating radial movement of a set of two or four dies. The process is suitable for producing short or long lengths of bar or tubing with various internal or external profiles.
- Because die failure has a major economic impact, die design, material selection, and production method are of major importance. A variety of die materials and manufacturing methods is available, including advanced material-removal and finishing processes.

KEY TERMS

Barreling
Closed-die forging
Cogging
Coining
Edging
End grain
Flash
Forgeability
Forging
Fullering
Hammers
Heading
Hot-twist test
Hubbing
Impression-die forging
Incremental forging
Isothermal forging
Net-shape forging
Open-die forging
Orbital forging
Piercing
Precision forging
Presses
Sizing
Swaging
Upsetting

BIBLIOGRAPHY

Altan, T., Ngaile, G., and Shen, G. (eds.), **Cold and Hot Forging: Fundamentals and Applications**, ASM International, 2005.

ASM Handbook, Vol. 14A: **Metalworking: Bulk Forming**, ASM International, 2005.

Blazynski, T.Z., **Plasticity and Modern Metal-forming Technology**, Elsevier, 1989.

Byrer, T.G. (ed.), **Forging Handbook**, Forging Industry Association, 1985.

Dieter, G.E., Kuhn, H.A., and Semiatin, S.L. (eds.), **Handbook of Workability and Process Design**, ASM International, 2003.

Fundamentals of Tool Design, 5th ed., Society of Manufacturing Engineers, 2003.

Hosford, W.F., and Caddell, R.M., **Metal Forming: Mechanics and Metallurgy**, 3rd ed., Cambridge, 2007.

Lange, K. (ed.), **Handbook of Metal Forming**, McGraw-Hill, 1985.

Product Design Guide for Forging, Forging Industry Association, 1997.

Tool and Manufacturing Engineers Handbook, 4th ed., Vol. 2, *Forming*, Society of Manufacturing Engineers, 1984.

Tschaetch, H., **Metal Forming Practice: Processes, Machines, *Tools***, Springer, 2007.

REVIEW QUESTIONS

14.1. What is the difference between cold, warm, and hot forging?

14.2. Explain the difference between open-die and impression-die forging.

14.3. Explain the difference between fullering, edging, and blocking.

14.4. What is flash? What is its function?

14.5. Why is the intermediate shape of a part important in forging operations?

14.6. Describe the features of a typical forging die.

14.7. Explain what is meant by "load limited," "energy limited," and "stroke limited" as these terms pertain to forging machines.

14.8. What type of parts can be produced by rotary swaging?

14.9. Why is hubbing an attractive alternative to producing simple dies?

14.10. What is the difference between piercing and punching?

QUALITATIVE PROBLEMS

14.11. How can you tell whether a certain part is forged or cast? Explain the features that you would investigate.

14.12. Identify casting design rules, described in Section 12.2, that also can be applied to forging.

14.13. Describe the factors involved in precision forging.

14.14. Why is control of the volume of the blank important in closed-die forging?

14.15. Why are there so many types of forging machines available? Describe the capabilities and limitations of each.

14.16. What are the advantages and limitations of (a) a cogging operation and (b) isothermal forging?

14.17. Describe your observations concerning Fig. 14.16.

14.18. What are the advantages and limitations of using die inserts? Give some examples.

14.19. Review Fig. 14.5d and explain why internal draft angles are larger than external draft angles. Is this also true for permanent-mold casting?

14.20. Comment on your observations regarding the grain-flow pattern in Fig. 14.12.

14.21. Describe your observations concerning the control of the final tube thickness in Fig. 14.15.

14.22. By inspecting some forged products, such as hand tools, you will note that the lettering on them is raised rather than sunk. Offer an explanation as to why they are made that way.

14.23. Describe the difficulties involved in defining the term "forgeability" precisely.

QUANTITATIVE PROBLEMS

14.24. Take two solid, cylindrical specimens of equal diameter, but different heights, and compress them (frictionless) to the same percent reduction in height. Show that the final diameters will be the same.

14.25. Calculate the forging force for a solid, cylindrical workpiece made of 1020 steel that is 90 mm high and 125 mm in diameter and is to be reduced in height by 30%. Let the coefficient of friction be 0.15.

14.26. Using Eq. (14.2), estimate the forging force for the workpiece in Problem 14.25, assuming that it is a complex forging and that the projected area of the flash is 30% greater than the projected area of the forged workpiece.

14.27. To what thickness can a cylinder of 5052-O aluminum that is 100 mm in diameter and 25 mm high be forged in a press that can generate 450 kN?

14.28. In Example 14.1, calculate the forging force, assuming that the material is 1100-O aluminum and that the coefficient of friction is 0.10.

14.29. Using Eq. (14.1), make a plot of the forging force, F, as a function of the radius, r, of the workpiece. Assume that the flow stress, Y_f, of the material is constant. Remember that the volume of the material remains constant during forging; thus, as h decreases, r increases.

14.30. How would you go about calculating the punch force required in a hubbing operation, assuming that the material is mild steel and the projected area of the impression is 320 mm^2. Explain clearly. (*Hint*: See Section 2.6 on hardness.)

14.31. A mechanical press is powered by a 23-kW motor and operates at 40 strokes per minute. It uses a flywheel, so that the crankshaft speed does not vary appreciably during the stroke. If the stroke is 150 mm, what is the maximum constant force that can be exerted over the entire stroke length?

14.32. Assume that you are an instructor covering the topics described in this chapter and you are giving a quiz on the numerical aspects to test the understanding of the students. Prepare two quantitative problems and supply the answers.

SYNTHESIS, DESIGN, AND PROJECTS

14.33. Devise an experimental method whereby you can measure only the force required for forging the flash in impression-die forging.

14.34. Assume that you represent the forging industry and that you are facing a representative of the casting industry. What would you tell that person about the merits of forging processes?

14.35. Figure P14.35 shows a round impression-die forging made from a cylindrical blank, as illustrated on the left. As described in this chapter, such parts are made in a sequence of forging operations. Suggest a sequence of intermediate forging steps to make the part on the right, and sketch the shape of the dies needed.

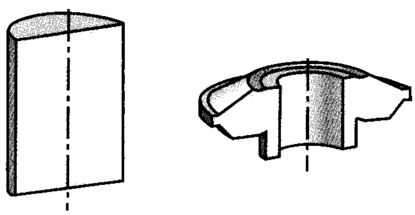


FIGURE P14.35

14.36. In comparing forged parts with cast parts, we have noted that the same part may be made by either process. Comment on the pros and cons of each process, considering factors such as part size, shape complexity, design flexibility, mechanical properties developed, and performance in service.

14.37. From the data given in Table 14.3, obtain the approximate value of the yield strength of the materials listed at hot-forging temperatures. Plot a bar chart showing the maximum diameter of a hot-forged part produced on a press with a 60-ton capacity as a function of the material.

14.38. Review the sequence of operations in the production of the stepped pin shown in Fig. 14.13. If the conical-upsetting step is not performed, how would the final part be affected?

14.39. Using a flat piece of wood, perform simple cogging operations on pieces of clay and make observations regarding the spread of the pieces as a function of the original cross sections (for example, square or rectangular with different thickness-to-width ratios).

14.40. Discuss the possible environmental concerns regarding the operations described in this chapter.