Forging in the conventional sense may be classified as (1) open-die (flat-tool) or smith forging, and (2) closed-die or impression-die forging. **Open-die forging** is the term applied to all forging operations, in which there is no lateral constraint except for friction and consequently no three-dimensional confinement. Sometimes the distinction between open- and closed-die forging is not too clear, such as, for example, in swaging and edging operations, in which a considerable amount of lateral confinement may occur.

Open-die or smith forging, which will be discussed here is done with a hand hammer, a power hammer, or a power press by use of tools or dies that are flat or nearly flat, in which the manipulation of the workpiece is done by hand or by a mechanical manipulator. This process is used (1) when the desired shape is simple, (2) when the quantity of forgings required is too small to justify the time and cost of making closed dies, (3) as a preliminary operation to closed-die forging to produce a forging multiple or preform of the required shape and size, (4) where the forging is too large to be forged in closed dies and (5) when, in some cases, the delivery date is too close, i.e., the lead time is too short to make the closed dies needed.

In some cases, the open-die forging is used in its final form as forged such as a crane hook with perhaps only a scale removal, or it may be rough machined, finished machined, heat treated, and finished ground to the final shape. Often, not only a considerable amount of machining is eliminated by open-die forging, but also much superior mechanical properties are imparted to the metal by breaking up the coarse, dendritic, cast microstructure, by welding voids and by proper metal flow.

The stock or forging multiple is usually cut by cold shearing or cold sawing. Often only one end of a long workpiece is inserted into the furnace for heating to the proper forging temperature, and the other cooler end is held with the hands or with tongs for forging and for shearing off after forging.

Open-Die Forging Operations

Some of the typical, principal open-die forging operations as shown in Fig. 1 are as follows:

a) Upsetting, involving compression between flat, overhanging dies. In upsetting (Fig.1,a) the cross-sectional area of the billet is increased due to a reduction in its height. By repeated upsetting from different sides the billet can be returned to its initial shape but the metal will be of higher quality and its properties will be uniform in all directions. The coefficient of forging reduction in upsetting in a single direction is calculated as the ratio of the initial to the final height or as the ratio of the final to the initial cross-sectional area.

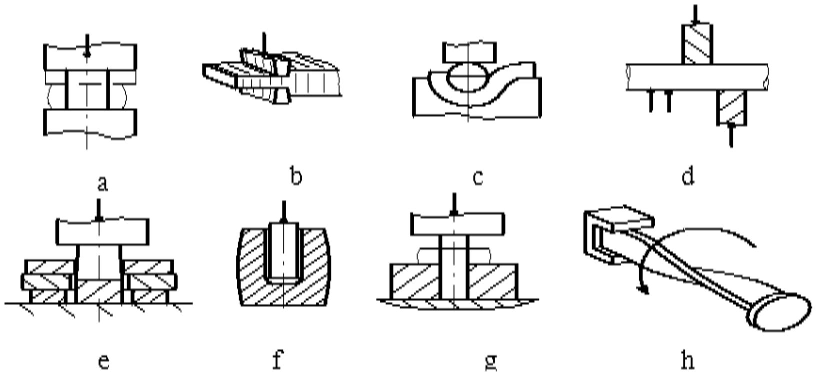


Fig. 1. Open-die forging operations

b) Cogging or drawing out, involving compression between narrow dies. Cogging is the systematic forging of an ingot to reduce it to a bloom, whereas drawing out is the elongation of any shape by systematically reducing its cross section. In drawing down the length of the billet is increased by reducing its cross-sectional area. The billet may be drawn down beginning either at the end or from the middle. If, in drawing down, the billet is turned 90° so that the blows of the tool are applied to both sides of the billet, the operation is called drawing down with turning. Because the contact area per stroke is small, a long section of a bar can be reduced in thickness without requiring large forces or machinery.

c) Bending of a workpiece between mating dies;

d) Shearing, involving severing with off-set dies;

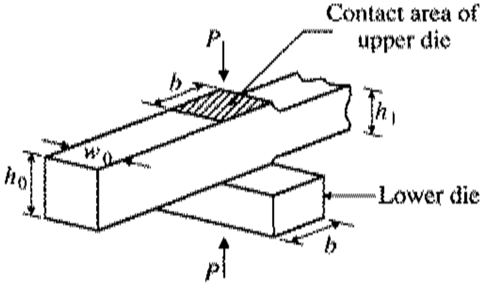
e) Punching, involving indenting (as in center punching) or perforating with mating rings or dies.

f) Piercing, involving impressing an indentation into the workpiece. Piercing with a punch is employed to obtain blind or through holes in the metal.

g) Heading, involving localized upsetting of the end of a workpiece between a confining or gripping die and a flat or contoured upsetting die (Fig. 1,g). Heading may be done by heating only a part of the billet (the end or the middle) or by restricting deformation of a section of the billet by means of a ring-shaped tool.

h) Twisting or torsion, as of a flat bar or V-eight crankshaft.

j) Swaging, involving compression between longitudinal, semicircular or semi-contoured dies



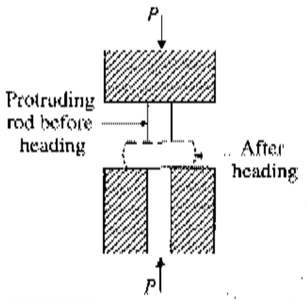
(*a*) Cogging or drawing out

i) Fullering, involving compression between rounded or convex dies to reduce a middle section of a bar

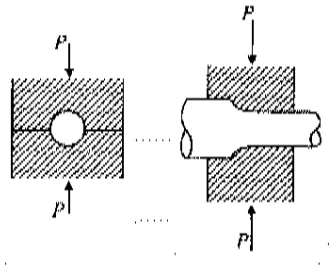
k) Edging, involving compression with concave dies to form an enlarged middle section of a bar and to distribute the metal to the desired shape

l) Extrusion forging:

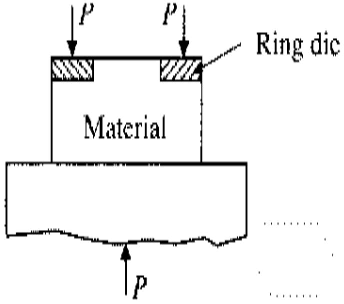
Simple forging or open-die forging can be done with a heavy hand hammer and an anvil. During such process a solid workpiece is placed between two flat dies and reduced in height by compressing it. This process is also called upsetting or flat-die forging.



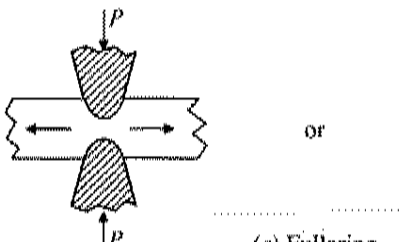
(c) Heading



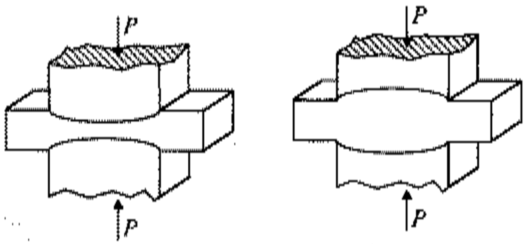
(*d*) Swaging



(*d*) Extrusion forging



(e) Fullering



(f) Edging

The die surfaces in open-die forging may have simple cavities to produce relatively simple forgings. Since a constant volume has to be maintained, any reduction in height increases the diameter of the part.

During upsetting the workpiece is deformed nonuniformly. In actual operations, the part develops a barrel shape, also known as pancaking. Barreling is caused primarily by frictional forces at the die-workpiece interfaces that oppose the outward flow of the materials at these interfaces. Thus barreling can be minimized if an effective lubricant is used. Barreling can also occur in upsetting hot workpieces between cold dies. The material at and near the interfaces cools rapidly, while the rest of the workpiece is relatively hot. Thus the material at the ends of the workpiece has greater resistance to deformation than at its center. Consequently, the central portion of the workpiece deforms to a greater extent than its ends. Barreling from thermal effects can be reduced or eliminated if heated dies or a thermal barrier, such as glass cloth at the die-workpiece interfaces, are used.

Simple forgings can be made by the open-die process. The large rotor for a steam turbine, for example, is made from a long cast ingot that is hot forged. The ingot, which may be square in cross-section, rests lengthwise on a flat die and is reduced in diameter a little at a time. The workpiece is rotated intermittently, with the use of large mechanical manipulators, after each step of deformation. This process is known as breaking down the cast ingot. It changes the microstructure of the workpiece from a cast to a wrought structure with smaller uniform grains and improved mechanical properties. Ring-shaped parts may also be reduced in thickness in this manner with the use of internal mandrel. Although most open-die forgings generally weigh 15 – 500 kg (30-1000 Lb), forgings as large as 300 tons have been made. Sizes may range from very small to 23 m (75 ft) long shafts in the case for ship propellers.

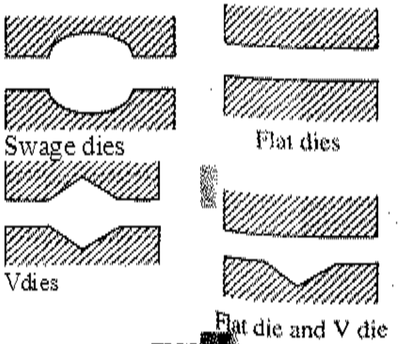


FIGURE 3
Four typical types of dies of simple shape commonly used in open-die forging.

The initial material in smith forging may be ingots, blooms or rolled billets of various cross sections and lengths.

The following topics pertaining to open-die (flat-tool) forging will be discussed next: (1) open-die forging operations, (2) cogging or drawing out by flat-tool forging, (3) axisymmetric compression of a short cylinder or disc between flat overhanging anvils,.

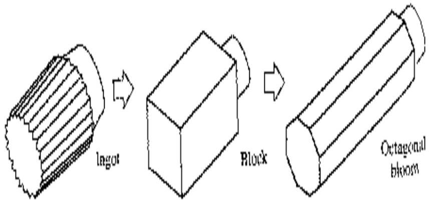


FIGURE 8.9
Forging sequence in open-die forging of an octagonal bloom from a fluted ingot. (*Courtesy of Forging Industry Association.*)

Cogging or Drawing Out by Flat-Tool Forging

The object of cogging or drawing out is to reduce the cross section of the workpiece in a stepwise sequence by moving the ingot, billet, or bar from one end toward the other during forging in what is called a *pass*. To reduce the workpiece in one pressing operation may require a very large force and/or also a very large press platen width, and consequently may be impracticable. Both the reduction in height A/i and the bite *b* shown in Fig. 12, should be as large as possible without causing such defects as laps. Several passes alternating on each pair of faces are usually required to complete the operation. Usually the forging procedure is left to the experienced operator or forgemaster; however, with recent emphasis on increasing production and automation, each operation must be programmed, examined and preplanned from an engineering point of view in order to optimize results.

Each compression or squeeze operation, resulting in a reduction in thickness, will cause the workpiece not only to elongate in length but also to spread in width as shown in Fig. 8.12. These two dimensional changes may be expressed in terms of the coefficient of spread, *S*, and the coefficient of elongation, 1-*S* as follows

$$S = \text{width elongation/thickness reduction} = \ln(w_1/w_0)/\ln(h_0/h_1)$$
$$1-S = \text{length elongation/thickness reduction} = \ln(l_1/l_0)/\ln(h_0/h_1)$$

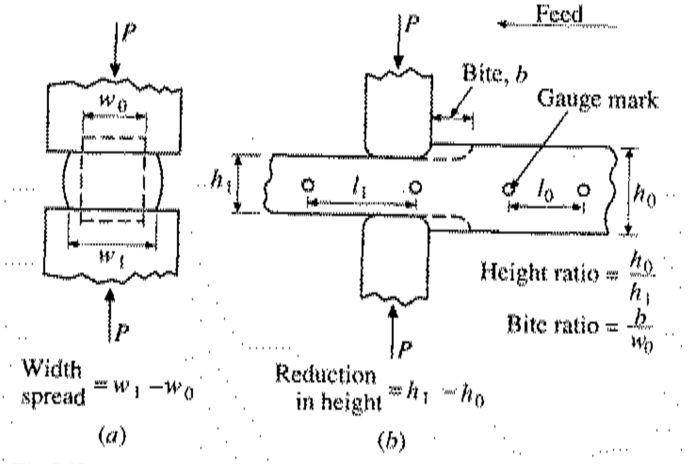


***Fig.* 8.12**
Nomenclature for cogging and drawing out of a rectangular workpiece (a) end view, and *(b)* side view

For hot, low-carbon steel, the bite ratio was the main factor influencing *S* as shown in Fig. 8.13, although the height ratio h_1/h_0 also exerted a small but statistically significant effect. The spread coefficient *S* as a function of the bite ratio b/W_0 as shown in Fig. 8.14, is given by

$$S = 0.14 + 0.36\left(\frac{b}{w_0}\right) - 0.054\left(\frac{b}{w_0}\right)^2$$

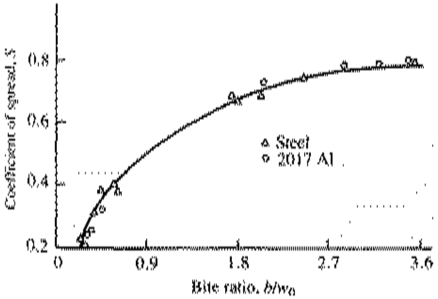


FIGURE 8.13

Relation between the coefficient of spread and the bite ratio for open-die forging of rectangular blocks

Axisymmetric Compression of a Short Cylinder or Disc Between Flat, Overhanging Platens

In the compression of a ductile cylindrical specimen with overhanging flat dies or platens, in addition to the extent of inhomogeneous deformation that may occur, the question of whether or not buckling will occur and the amount and type of friction that exists must also be considered. Let us first dispense briefly with the problem of buckling.

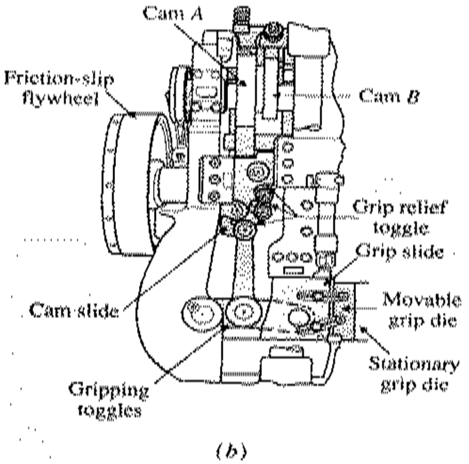


FIGURE 8.15

Cutaway top view of the forging machining. Cam *A* closes the movable grip die and cam *B* opens it. The heading tools are not shown,

The maximum, initial height-to-diameter ratio that can be successfully used in upsetting is important in conjunction with the operation of the horizontal upset forging machine or upsetter (Fig. 8.15). This ratio should not exceed two or two and one-half at the most, when an unsupported cylindrical specimen or workpiece is compressed with flat dies, otherwise lateral buckling or skewing will occur as shown in Fig. 8.16. The actual maximum limit that may be used may be found experimentally, and it depends on such factors as the accuracy with which the ends are cut, the parallelism of the die surfaces, the surface finish and lubricity of the faces, etc.

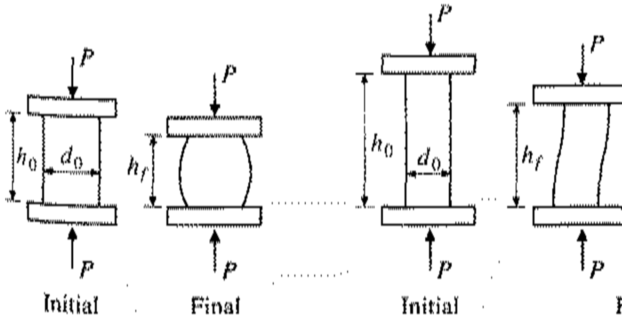


Fig. 8.16. The effect of the maximum height-to-diameter ratio (aspect ratio) on the mode of upsetting of a right, circular cylinder in compression between flat, parallel, overhanging anvils, (a) If $h_0/d_0 \leq 2$ to 2.5, the cylinder upsets successfully, and (b) if $h_0/d_0 \geq 2$ to 2.5,, the cylinder skews or buckles as shown.

Since in an upsetter the stock is gripped firmly at one end and may be enclosed in a cavity which modifies buckling at the other, somewhat greater lengths can be upset than by flat, parallel die upsetting. The following three design rules illustrated in Fig. 8.17 should be followed in designing parts that are to be upset forged :

1. The limiting length of unsupported metal that can be upset in one blow without buckling is three times the diameter of the bar
2. Lengths of stock greater than three times the diameter may be upset successfully provided that the diameter of the die cavity is not more than $1\frac{1}{2}$ times the diameter of the bar
3. In an upset requiring stock with a length greater than three times the diameter of the bar and where the diameter of the upset is less than $1\frac{1}{2}$ times the diameter of the bar, the length of unsupported metal beyond the face of the die must not exceed the diameter of the bar

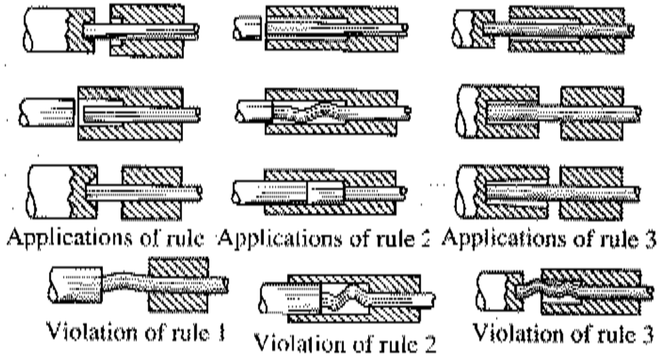


FIGURE 8.17

Design rules governing upset forging.

The amount and nature of the localized deformation or flow localization resulting from the inhomogeneous deformation may be analyzed by use of a number of different macroscopic methods to study the sectioned specimen such as by measuring the distortion of a grid pattern, obtaining the hardness gradient, etching of the cold-worked metal, etching of the recrystallized cold-worked metal, etc.

In the grid or visioplastic method, fine ductile wires may be threaded through small axial and/or diametral holes equally, or regularly spaced so as to form a grid on the diametral, axial plane of the specimen. Also, a higher melting-point wire grid may be cast into a lower-melting-point metal such as, for example, a copper grid in an aluminum alloy.

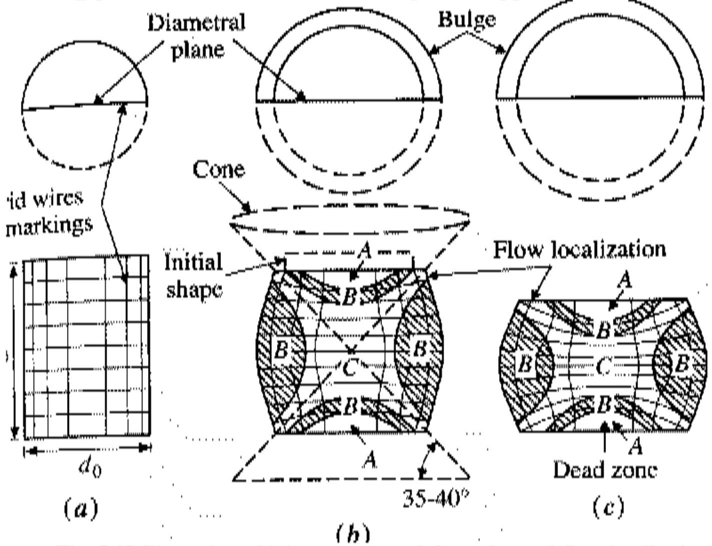


Fig. 8.18 Illustration of inhomogeneous deformation and flow localization in compression of a right, circular cylinder with overhanging anvils and with interface friction showing a cross section of a diametral plane of (a) the undeformed cylinder, *(b)* the distortion of the grid pattern and the region of variable deformation (region *A* the least and C the most), and (c) the final cylinder showing barreling

After deformation the specimen is sectioned along a diametral plane and ground on a fine abrasive belt or wheel to expose the wires. A schematic representation of such a grid pattern before and after deformation is shown in Fig. 8.18. As is illustrated in the figure, the material adjacent to the platens in region *A* remains virtually undeformed and behaves as a rigid metal "cone" or dead zone as it penetrates into the specimen. The cones approximately coincide with the surfaces of maximum shear, but their base angles are between 35 and 40° rather than 45°, and decrease as the height of the specimen becomes less than the diameter. The bulk of the deformation or flow localization occurs in region C with the greatest deformation occurring at the center of the cylinder and a lesser amount in region *B*.

As the specimen is deformed, because of the interfacial friction between the metal and the platen, the material located in the central part of the specimen flows more readily than that in the immediate vicinity of the platen or die, causing the cylinder to become barrel-shaped. The degree of barreling developed for a given reduction of height increases with the frictional resistance at the material-platen interface. For sticking friction, if the h_o/d_o ratio and the reduction are high enough, the cylindrical surface folds over or is inverted so as to become a peripheral-ring on the ends of the deformed specimen. If the cylindrical surface is tarnished or oxidized and the ends are polished prior to deformation, a dark peripheral ring can be seen on the ends of the specimen after deformation as shown in Fig. 8.19.

The size of the slip zone goes through a maximum during the compression of a tall cylinder, i.e., one with a *ho/do* ratio of 1.5 to 2.2. During initial compression, the slip zone first grows by inversion as discussed above. Then, as compression is continued the specimen begins to deform as a short rather than a tall cylinder. As the cylinder slides over the platen, the slip cone shrinks in size. The metal at the center flows outward and the center is in tension until the upper and lower dead-metal zones begin to interact, then they begin to deform and the stresses at the center become entirely compressive as shown graphically in Fig. 8.20.

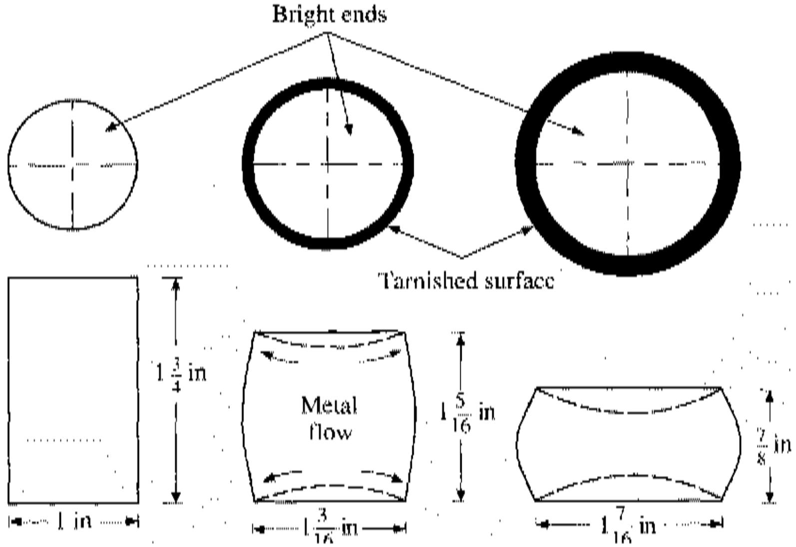
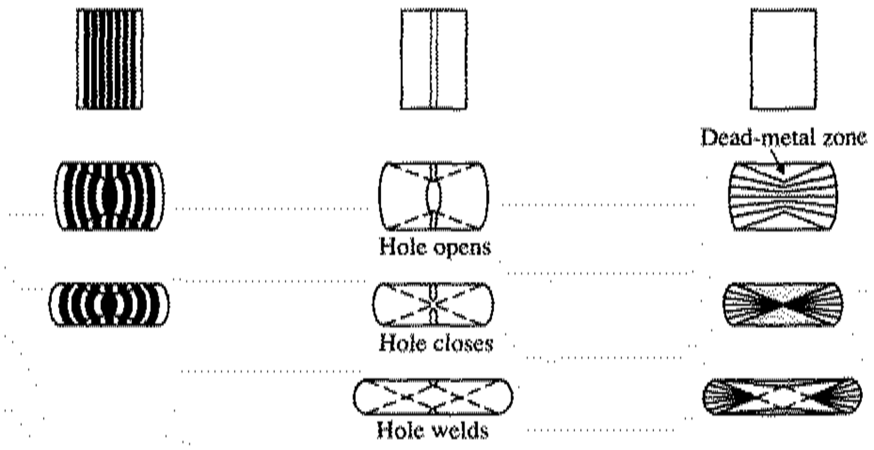


FIGURE 8.19

Schematic drawings showing the flow of metal by inversion during compression of a tall cylinder with sticking friction at the platen-workpiece interface. The tarnished, peripheral ring on the ends is maximum for sticking friction and decreases with the reduction in friction until it disappears for the frictionless case



(A) Deformation pattern in *(B)* Deformation pattern in (C) Distribution of deformation upset
billet with upset billet with based on *A* and *B* inserted grid rods center hole

FIGURE 8.20
Deformation patterns in cylindrical billet upset forged between flat, parallel dies

As the *ho/do* ratio is progressively decreased, the dead zones do not meet and interpenetrate as is sometimes thought, but they progressively flatten. In very short cylinders, they not only flatten but also begin to decrease in diameter when the *h/d* ratio falls below a certain minimum value.

If the hardness is taken of the cross section shown in Fig. 8.18 of a cold-forged cylinder, the strainhardening will be nil in zone *A,* it will increase through the intermediate zone *B,* and it will be a maximum in zone *C.* When care is taken to reduce the friction to a minimum at the platen-metal interface, so that the deformation is practically homogeneous, the difference in strainhardening is virtually absent.

LUBRICATION IN METALWORKING PROCESSES

8.3.1 Introduction

Lubrication for metalworking is usually classified as (1) hydrodynamic, (2) boundary, (3) extreme pressure, and (4) solid film, although the distinction between the classes is not always clear.

Commercial lubricants may also be classified into two broad categories: (1) wet and (2) dry.

Wet lubricants include

1. Pure vegetable or mineral oil
2. Oils with fatty acids and extreme pressure additives
3. Oil, or water-based solid-phase lubricants

Dry lubricants include

1. Solid-phase lubricants carried in volatile solvents
2. Polymeric materials
3. Waxes

In hydrodynamic lubrication a liquid lubricant such as mineral oil may be "dragged" into the interface between workpiece and die by their rapid relative motion such as in wiredrawing and extrusion, thereby effecting a full separation between them. Some lubricants such as **fatty acids** like oleic that form solid metallic soaps with the metal, are remarkably effective as very thin films. Since under certain conditions they are worn away, they are called *boundary lubricants.* Some of these lubricants are compounds that contain S, Cl, and P, such as chlorinated paraffin (50% Cl), and can withstand very high pressures during operation and are called *extreme pressure lubricants.* Any solid film, that has a lower shear strength than the metallic workpiece, can be used as a solid lubricant such as copper, lead, graphite, molybdenum disulphide (MoS_2) (trade name Molykote).

Some of the functions of a good lubricant in metalworking are (1) reduce friction, (2) reduce die wear, (3) prevent metal pickup on the tool surfaces or seizing, (4) provide thermal insulation between the workpiece and the die surface in order to prevent excessive heat loss of the former and excessive heating of the latter, (5) cool the workpiece in some cases to prevent overheating of the workpiece due to the heat generated during working, and (6) control surface finish of the workpiece.

Some of the requirements of a lubricant in metalworking are (1) they must withstand the working conditions of pressure and temperature, (2) they must not deteriorate in service and storage, (3) they must be easy to apply and remove and not leave an objectionable residue, and (4) they must be safe, nontoxic, and not otherwise objectionable for use.

Since the cost of the dies is 10 to 20 percent of the cost of the forgings, lubrication is an important factor in hot forging and similar processes.

Heading

Heading is essentially an upsetting operation, usually performed at the end of a round rod or wire in order to produce a larger cross-section. Typical examples are the heads of bolts, screws, rivets, nails, and other fasteners (Fig. 14.12). Heading processes can be carried out cold, warm, or hot. They are performed on machines called *headers,* which are usually highly automated, with production rates of hundreds of pieces per minute for small parts. These machines tend to be noisy; thus soundproof enclosures or the use of ear protectors may be required. Heading operations can be combined with cold-extrusion processes (see Section 15.5) to make various parts.

An important aspect of heading is the tendency for the bar to buckle if its unsupported length-to-diameter ratio is too high. This ratio is usually limited to less than 3:1 but can be higher, depending on die geometry. For example, greater ratios can be accommodated if the diameter of the die cavity is not more than 1.5 times the diameter of the bar.

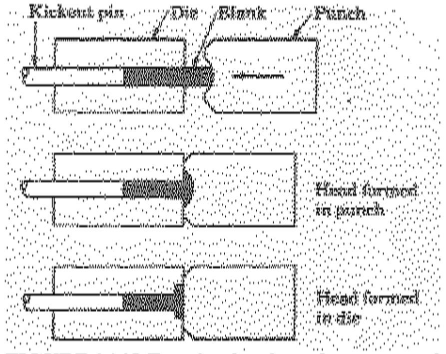


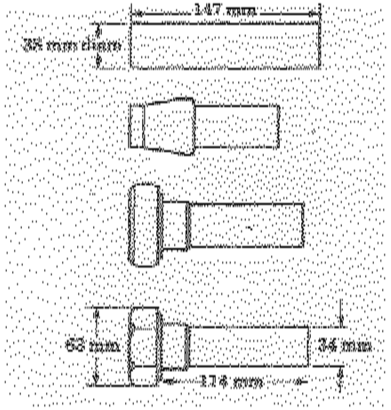
FIGURE 14.12 Forming heads on fasteners such as bolts and rivets. These processes are called heading.

Example: Manufacturing of a bolt by heading operations.

The starting material for the steel bolt shown in the accompanying figure is a round rod 147 mm (5.8 in.) long and 38 mm (1.5 in.) in diameter, sheared from a long drawn rod. The first operation consists of preforming by gathering material at one end of the rod to prepare it for heading. The second operation produces a round head, while reducing the long section to 34 mm (1.34 in.). The last operation produces a hexagonal head. All operations are performed at room temperature, thus cold working the material, improving its mechanical properties, and producing a good surface finish.

14.4.2 Piercing

Piercing is a process of indenting—but not breaking through—the surface o workpiece with a punch in order to produce a cavity or an impression (Fig. 14.13 The workpiece may be confined in a die cavity, or it may be unconstrained. Piercing may be followed by punching to produce a hole in the part (see Fig. 13.16). Piercing is also performed to produce hollow regions in forgings (Fig. 14.14;



The *piercing force* depends on the punch's cross-sectional area and it's geometry, the strength of the material, and friction. The pressure may range from three to five times the strength of the material, or the same level of stress required to make an indentation in hardness testing

Forgeable Metals[1]

An almost unlimited variety of forging metals is available in ferrous and nonferrous alloys. The following are general classifications of forgeable metals. An exhaustive treatment may be found in books on forging and metallurgy.

1. Carbon steels:

a. Low-carbon (up to 0.25 percent) – forgings for moderate conditions and for carburized parts where resistance to abrasion is important.

b. Medium-carbon (0.30 to 0.50 percent) – forgings for more severe service. Some heat treatment is generally desirable.

c. High-carbon (above 0.50 percent)—forgings for hard surfaces and for springs. Heat treatment is essential.

2. Alloy steels (manganese, nickel, nickel-chromium, molybdenum, chromium, vanadium, chromium-vanadium, tungsten, silicon-manganese).

3. Corrosion- and heat-resisting steels and stainless steels: Generally, but not necessarily, forged surfaces should be polished to obtain the full benefit of corrosion-resisting properties.

4. Iron: Either wrought iron or ingot iron is forged for special applications where ductility is required. Wrought iron furnishes a moderate degree of corrosion resistance. The copper-bearing irons and low-carbon steels are in this class.

5. Copper, brasses, and bronzes.

6. Nickel and nickel-copper alloys: Pure nickel is forgeable. The alloy of nickel and copper known as Monel metal offers a desirable combination of strength, toughness, and corrosion resistance.

7. Light alloys (aluminum, magnesium).

8. Titanium alloys.

Note that any ductile metal can be forged. The material is selected primarily for its ultimate properties in the part, such as corrosion resistance, strength, durability, and machinability. The forging process is a secondary consideration. It can be used as long as the high tooling cost can be spread over a large number of pieces.