Chapter Seven: Metal Forming - Forging

7.1. Introduction

Forging is a deformation process in which the work is compressed between two dies, using either impact or gradual pressure to form the part. It is the oldest of the metal forming operations, dating back to perhaps 5000 BCE (Historical Note 7.2). Today, forging is an important industrial process used to make a variety of high - strength components for automotive, aerospace, and other applications. These components include engine crankshafts and connecting rods, gears, air craft structural components, and jet engine turbine parts. In addition, steel and other basic metals industries use forging to establish the basic form of large components that are subsequently machined to final shape and dimensions.

7.1. Historical Note

The forging process dates from the earliest written records of man, around 7000 years ago. There is evidence that forging was used in ancient Egypt, Greece, Persia, India, China, and Japan to make weapons, jewelry, and a variety of implements. Craftsmen in the art of forging during these times were held in high regard. Engraved stone platens were used as impression dies in the hammering of gold and silver in ancient Crete round 1600 BCE. This evolved into the fabrication of coins by a similar process around 800 BCE. More complicated impression dies were used in Rome around 200 CE. The blacksmith’s trade remained relatively unchanged for many centuries until the drop hammer with guided ram was introduced near the end of the eighteenth century. This development brought forging practice into the Industrial Age.

Forging is carried out in many different ways. One way to classify the operations is by working temperature. Most forging operations are performed hot or warm, owing to the significant deformation demanded by the process and the need to reduce strength and increase ductility of the work metal. However, cold forging is also very common for certain products. The advantage of cold forging is the increased strength that results from strain hardening of the component.

Either impact or gradual pressure is used in forging. The distinction derives more from the type of equipment used than differences in process technology. A forging machine that applies an impact load is called a ***forging hammer***, while one that applies gradual pressure is called a ***forging press***.

Another difference among forging operations is the degree to which the flow of the work metal is constrained by the dies. By this classification, there are three types of forging operations, shown in Figure 7.1: (a) open-die forging, (b) impression-die forging, and (c) flashless forging. In ***open-die forging***, the work is compressed between two flat (or almost flat) dies, thus allowing the metal to flow without constraint in a lateral direction relative to the die surfaces. In ***impression-die forging***, the die surfaces contain a shape or impression that is imparted to the work during compression, thus constraining metal flow to a significant degree. In this type of operation, a portion of the work metal flows beyond the die impression to form ***flash***, as shown in the figure. Flash is excess metal that must be trimmed off later. In ***flashless forging*** , the work is completely constrained within the die and no excess flash is produced. The volume of the starting workpiece must be controlled very closely so that it matches the volume of the die cavity.

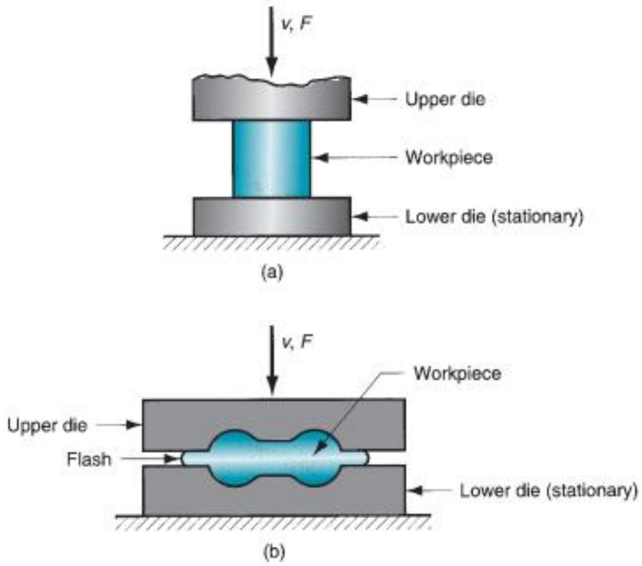

Figure 7.1 Three types of forging operation illustrated by cross-sectional sketches:

(a) open-die forging, (b) impression-die forging, and (c) flashless forging.

7.3. Open-Die Forging

The simplest case of open-die forging involves compression of a workpart of cylindrical cross section between two flat dies, much in the manner of a compression test (Section 3.1.2). This forging operation, known as ***upsetting*** or ***upset forging***, reduces the height of the work and increases its diameter.

- **Analysis of Open-Die Forging** If open- die forging is carried out under ideal conditions of no friction between work and die surfaces, then homogeneous deformation occurs, and the radial flow of the material is uniform throughout its height, as pictured in Figure 7.2. Under these ideal conditions, the true strain experienced by the work during the process can be determined by

$$\epsilon = \ln \frac{h_o}{h} \tag{7.1}$$

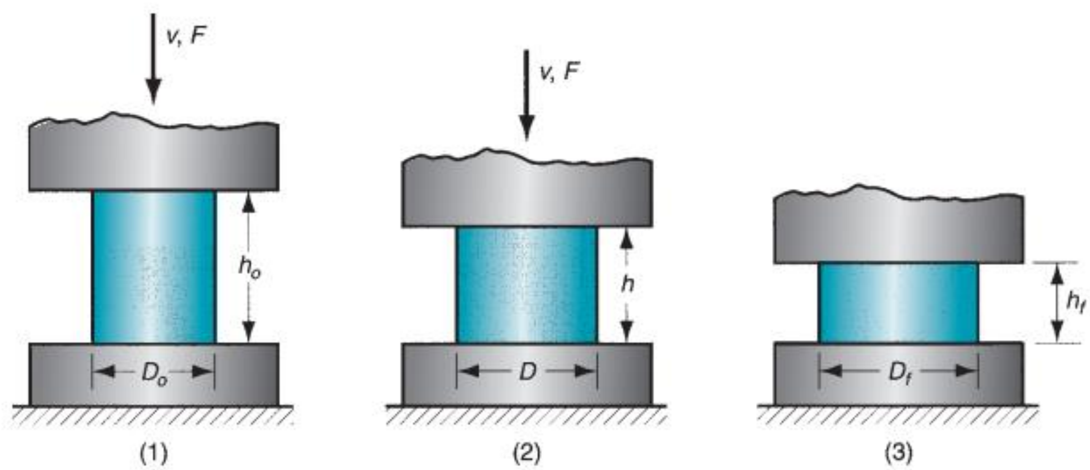

Figure 7.2 Homogeneous deformation of a cylindrical workpart under ideal conditions in an open-die forging operation: (1) start of process with workpiece at its original length and diameter, (2) partial compression, and (3) final size

where h_0= starting height of the work, mm (in); and h= the height at some intermediate point in the process, mm (in). At the end of the compression stroke, h= its final value h_f, and the true strain reaches its maximum value.

Estimates of force to perform upsetting can be calculated. The force required to continue the compression at any given height *h* during the process can be obtained by multiplying the corresponding cross-sectional area by the flow stress:

$$F = Y_f A \tag{7.2}$$

where F= force, lb (N); A=cross-sectional area of the part, mm^2 (in^2); and Y_f = flow stress corresponding to the strain given by Equation (7.1), MPa (lb/in^2). Area A continuously increases during the operation as height is reduced. Flow stress Y_f also increases as a result of work hardening, except when the metal is perfectly plastic (e.g., in hot working). In this case, the strain-hardening exponent n = 0, and flow stress Y_f equals the metal's yield strength Y. Force reaches a maximum value at the end of the forging stroke, when both area and flow stress are at their highest values.

An actual upsetting operation does not occur quite as shown in Figure 7.2 because friction opposes the flow of work metal at the die surfaces. This creates the barreling effect shown in Figure 7.3. When performed on a hot workpart with cold dies, the barreling effect is even more pronounced. This results from a higher coefficient of friction typical in hot working and heat transfer at and near the die surfaces, which cools the metal and increases its resistance to deformation. The hotter metal in the middle of the part flows mor readily than the cooler metal at the ends. These effects are more significant as the diameter-to-height ratio of the workpart increases, due to the greater contact area at the work–die interface.

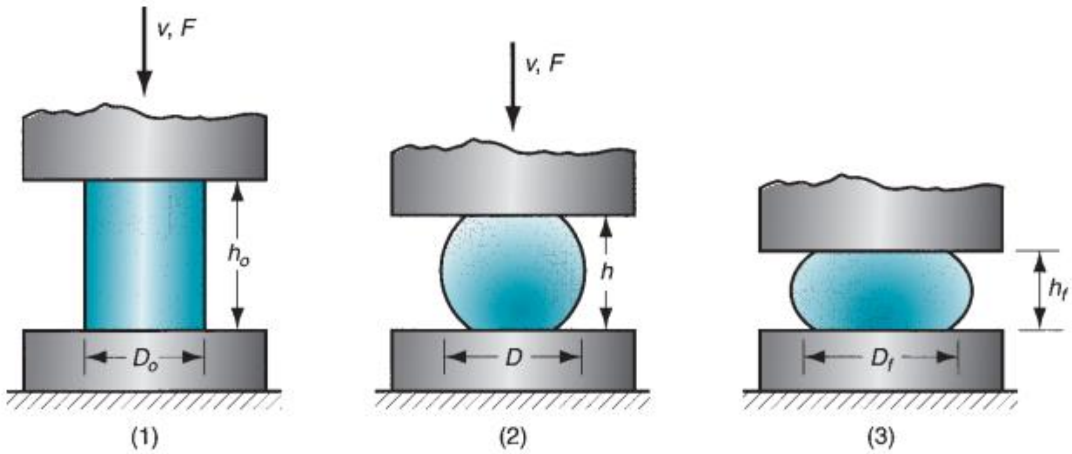

Figure 7.3 Actual deformation of a cylindrical workpart in open-die forging, showing pronounced barreling: (1) start of process, (2) partial deformation, and (3) final shape.

All of these factors cause the actual upsetting force to be greater than what is predicted by Equation (7.2). As an approximation, we can apply a shape factor to Equation (7.2) to account for effects of the *D/h* ratio and friction:

$$F = K_f Y_f A \tag{7.3}$$

where F, Y_f, and A have the same definitions as in the previous equation; and K_f is the forging shape factor, defined as

$$K_f = 1 + \frac{0.4\,\mu D}{h} \tag{7.4}$$

where μ = coefficient of friction; D = work part diameter or other dimension representing contact length with die surface, mm (in); and h = workpart height, mm (in).

Example: A cylindrical workpiece is subjected to a cold upset forging operation . The starting pieces 75 mm in height and 50 mm in diameter. It is reduced in the operation to a height of 36 mm. The work material has a flow curve defined by K = 350 MPa and n = 0.17. A ssume a coeff icient of friction of 0.1. Determine the force as the process begins, at intermediate heights of 62 mm, 49 mm, and at the final height of 36 mm.

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Solution:

Workpiece volume $V = 75\ \pi(50^2/4)$=147,262 mm^3. At the moment contact is made by the upper die, h = 75 mm and the force F = 0. At the start of yielding, h is slightly less than 75 mm, and we assume that strain = 0.002, at which the flow stress is

$$Y_f = K\epsilon^n = 350(0.002)^{0.17} = 121.7 \text{ MPa}$$

The diameter is still approximately D = 50 mm and area $A = \pi(50^2/4)$=1963.5 mm^2.For these conditions, the adjustment factor K_f is computed as

$$K_f = 1 + \frac{0.4(0.1)(50)}{75} = 1.027$$

The forging force is

$$F = 1.027(121.7)(1963.5) = 245,410 \text{ MPa}$$

At h = 62 mm,

$$\epsilon = \ln\frac{75}{62} = \ln(1.21) = 0.1904$$

$$Y_f = 350(0.1904)^{17} = 264.0\ \text{MPa}$$

Assuming constant volume, and neglecting barreling,

$$A = 147,262/62 = 2375.2\ \text{mm}^2 \text{ and } D = \sqrt{\frac{4(2375.2)}{\pi}} = 55.0\ \text{mm}$$

$$K_f = 1 + \frac{0.4(0.1)(55)}{62} = 1.035$$

$$F = 1.035(264)(2375.2) = 649,303\ \text{N}$$

Similarly, at h = 49 mm, F = 955,642 N; and at h = 36 mm, F = 1,467,422 N. The load-stroke curve in Figure 7.4 was developed from the values in this example.

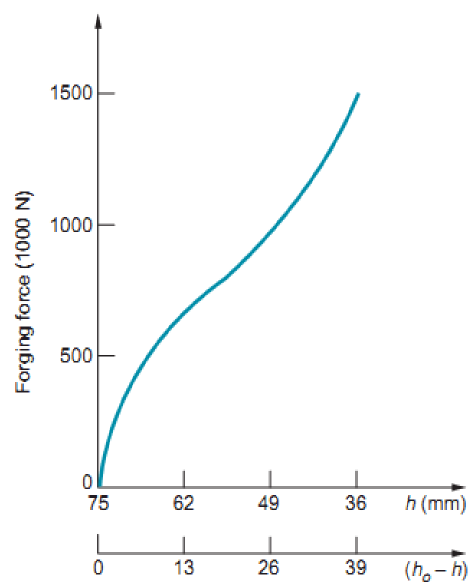

Figure 7.4 Upsetting force as a function of height h and height reduction ($h_0 - h$). This plot is sometimes called the load stroke curve.

- **Open-Die Forging Practice** Open-die hot forging is an important industrial process. Shapes generated by open-die operations are simple; examples include shafts, disks, and rings. In some applications, the dies have slightly contoured surfaces that help to shape the work. In addition, the work must often be manipulated (e.g., rotating in steps) to effect the desired shape change. Skill of the human operator is a factor in the success of these operations. An example of open-die forging in the steel industry is the shaping of a large square cast ingot into a round cross section. Open-die forging operations produce rough forms, and subsequent operations are required to refine the parts to final geometry and dimensions. An important contribution of open-die hot-forging is that it creates a favorable grain flow and metallurgical structure in the metal.

  Operations classified as open-die forging or related operations include fullering, edging, and cogging, illustrated in Figure 7.5. ***Fullering*** is a forging operation per-formed to reduce the cross section and redistribute the metal in a workpart in preparation for subsequent shape forging. It is accomplished by dies with convex surfaces. Fullering die cavities are often designed into multi-cavity impression dies, so that the starting bar can be rough formed before final shaping. ***Edging*** is similar to fullering, except that the dies have concave surfaces

  A ***cogging*** operation consists of a sequence of forging compressions along the length of a workpiece to reduce cross section and increase length. It is used in the steel industry to produce blooms and slabs from cast ingots. It is accomplished using open dies with flat or slightly contoured surfaces. The term incremental forging is sometimes used for this process.

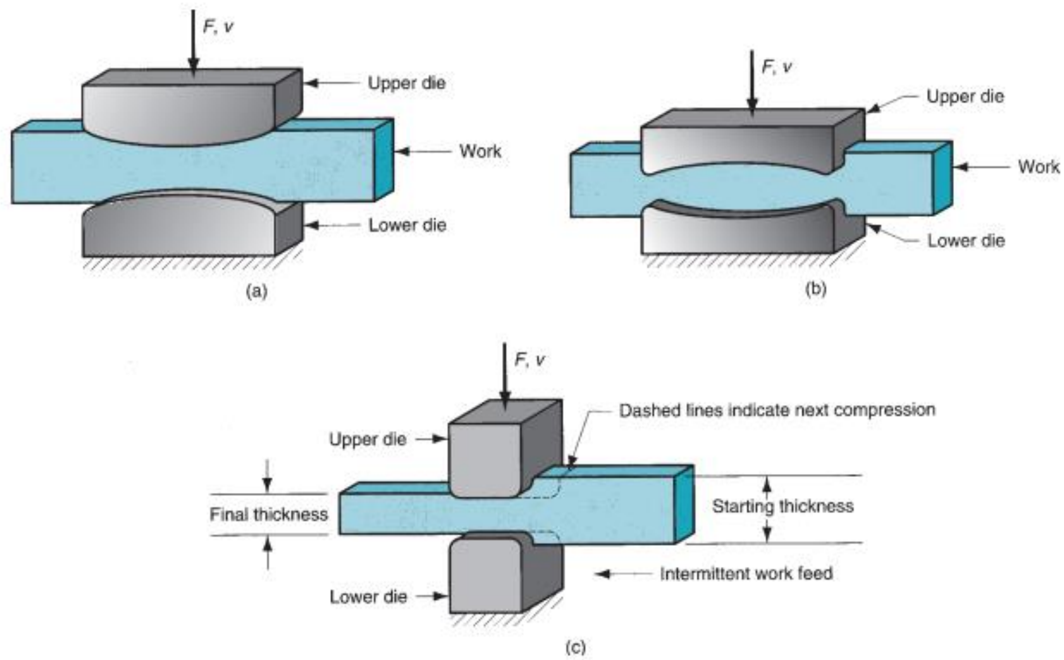

Figure 7.5 Several open-die forging operations:

(a) fullering, (b) edging, and (c) cogging.

7.4. Impression-Die Forging

Impression-die forging, sometimes called ***closed-die forging***, is performed with dies that contain the inverse of the desired shape of the part. The process is illustrated in a three-step sequence in Figure 7.6. The raw workpiece is shown as a cylindrical part similar to that used in the previous open-die operation. As the die closes to its final position, flash is formed by metal that flows beyond the die cavity and in to the small gap between the die plates. Although this flash must be cut away from the part in a subsequent trimming operation, it actually serves an important function during impression-die forging. As the flash begins to form in the die gap, friction resists continued flow of metal into the gap, thus constraining the bulk of the work material to remain in the die cavity. I n hot forging, metal flow is further restricted because the thin flash cools quickly against the die plates, thereby increasing its resistance to deformation. Restricting metal flow in the gap causes the compress ion pressures on the part to increase significantly, thus forcing the material to fill the sometimes intricate details of the die cavity to ensure a high-quality product.

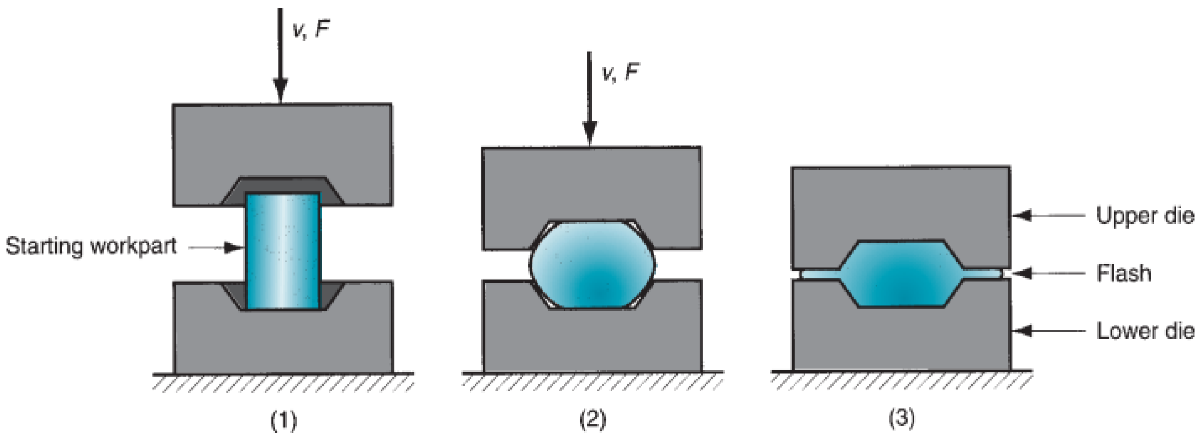

Figure 7.6 Sequence in impression-die forging: (1) just prior to initial contact with raw workpiece, (2) partial compression, and (3) final die closure, causing flash to form in gap between die plates.

Table 7.1 Typical K_f values part shapes in impression – die and flashless forging

TABLE 19.1 Typical K_f values for various part shapes in impression-die and flashless forging.

Part Shape	K_f	Part Shape	K_f
Impression-die forging:		Flashless forging:	
Simple shapes with flash	6.0	Coining (top and bottom surfaces)	6.0
Complex shapes with flash	8.0	Complex shapes	8.0
Very complex shapes with flash	10.0		

Several forming steps are often required in impression-die forging to transform the starting blank into the desired final geometry. Separate cavities in the die are needed for each step. The beginning steps are designed to redistribute the metal in the workpart to achieve a uniform deformation and desired metallurgical structure in the subsequent steps. The final steps bring the part to its final geometry. In addition, when drop forging is used, several blows of the hammer may be required for each step. When impression-die drop forging is done manually, as it often is, considerable operator skill is required under adverse conditions to achieve consistent results.

Because of flash formation in impression-die forging and the more complex part shapes made with these dies, forces in this process are significantly greater and more difficult to analyze than in open-die forging. Relatively simple formulas and design factors are often used to estimate forces in impression-die forging. The force formula is the same as previous Equation (7.3) for open-die forging, but its interpretation is slightly different:

$$F = K_f Y_f A \tag{7.5}$$

where F = maximum force in the operation, N (lb); A = projected area of the part including flash, mm^2 (in^2); Y_f = flow stress of the material, MPa (lb/in^2); and K_f = forging shape factor. In hot forging, the appropriate value of Y_f is the yield strength of the metal at the elevated temperature. In other cases, selecting the proper value of flow stress is difficult because the strain varies throughout the workpiece for complex shapes. K_f in Equation (7.5) is a factor intended to account for increases in force required to forge part shapes of various complexities. Table 7.1 indicates the range of values of K_f for different part geometries. Obviously, the problem of specifying the proper K_f value for a given workpart limits the accuracy of the force estimate.

Equation (7.5) applies to the maximum force during the operation, since this is the load that will determine the required capacity of the press or hammer used in the operation. The maximum force is reached at the end of the forging stroke, when the projected area is greatest and friction is maximum.

Impression-die forging is not capable of close tolerance work, and machining is often required to achieve the accuracies needed. The basic geometry of the part is obtained from the forging process, with machining performed on those portions of the part that require precision finishing (e.g., holes, threads, and surfaces that mate with other components). The advantages of forging, compared to machining the part completely, are higher production rates, conservation of metal, greater strength, and favorable grain orientation of the metal that results from forging. A comparison of the grain flow in forging and machining is illustrated in Figure 7.7.

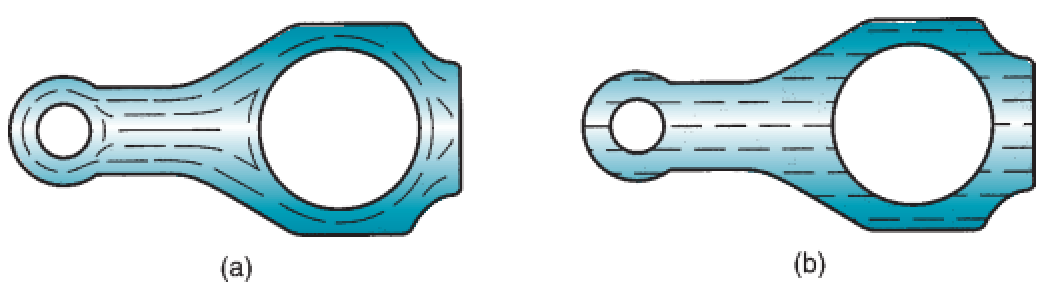

Figure 7.7 Comparison of metal grain flow in a part that is:

(a) hot forged with finish machining, and (b) machined complete.

Improvements in the technology of impression-die forging have resulted in the capability to produce forgings with thinner sections, more complex geometries, drastic reductions in draft requirements on the dies, closer tolerances, and the virtual elimination of machining allowances. Forging processes with these features are known as ***precision forging***. Common work metals used for precision forging include aluminum and titanium. A comparison of precision and conventional impression-die forging is presented in Figure 7.8.

Note that precision forging in this example does not eliminate f lash, although it reduces it.

Some precision f or gin g operations are accomplished without producing flash. Depending on whether machining is required to finis h the part geometry, precision forgings are properly classified as ***near net shape*** or ***net shape*** processes.

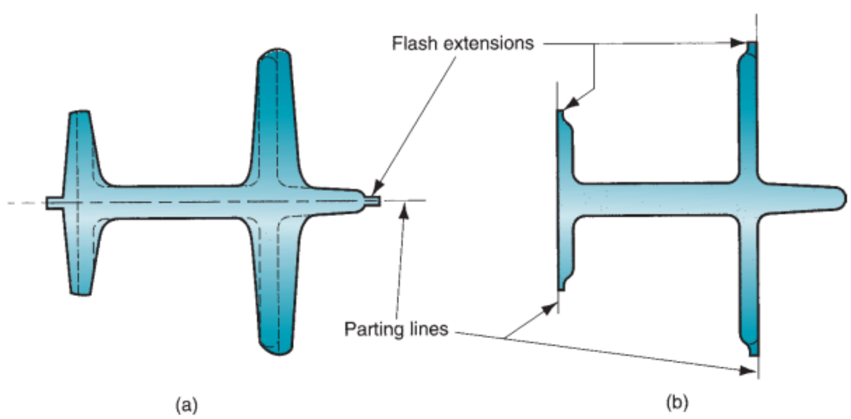

Figure 7.8 Cross sections of (a) conventional-and (b) precision forgings. Dashed lines in (a) indicate subsequent machining required to make the conventional forging equivalent in geometry to the precision forging. In both cases, flash extensions must be trimmed.

7.5. Flashless Forging

As mentioned above, impression-die forging is sometimes called closed-die forging in industry terminology. However, there is a technical distinction between impression-die forging and true closed-die forging. The distinction is that in closed-die forging, the raw workpiece is completely contained within the die cavity during compression, and no flash is formed. The process sequence is illustrated in Figure 7.9. The term ***flashless forging*** is appropriate to identify this process.

Flashless forging imposes requirements on process control that are more demanding than impression-die forging. Most important is that the work volume must equal the space in the die cavity with in a very close tolerance. If the starting blank is too large, excessive pressures may cause damage to the die or press. If the blank is too small, the cavity will not be filled. Because of the special demands made by flash less forging, the process lends itself best to part geometries that are usually simple and symmetrical, and to work materials such as aluminum and magnesium and their alloys. Flashless forging is often classified as a ***precision forging*** process.

Forces in flashless forging reach values comparable to those in impression-die forging. Estimates of these forces can be computed using the same methods as for impression-die forging: Equation (7.5) and Table 7.1.

Coining is a special application of closed-die forging in which fine details in the die are impressed into the top and bottom surfaces of the workpart. There is little flow of metal in coining, yet the pressures required to reproduce the surface details in the die cavity are high, as indicated by the value of K_f in Table 7.1. A common application of coining is, of course, in the minting of coins, shown in Figure 7.10. The process is also used to provide good surface finish and dimensional accuracy on workparts made by other operations.

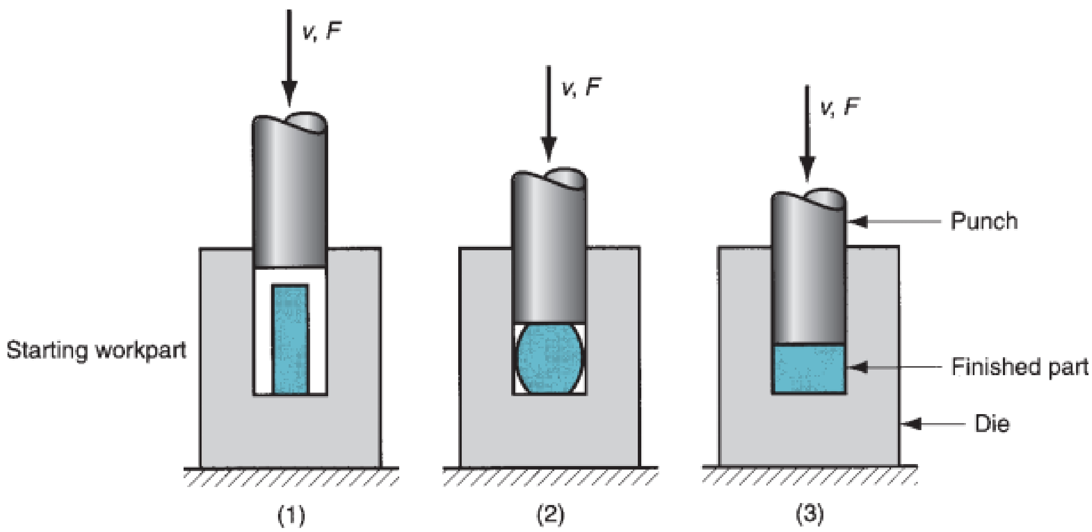

Figure 7.9 Flashless forging: (1) just before initial contact with workpiece, (2) partial compression, and (3) final punch and die closure. Symbols *v* and *F* indicate motion (*v* = velocity) and applied force, respectively.

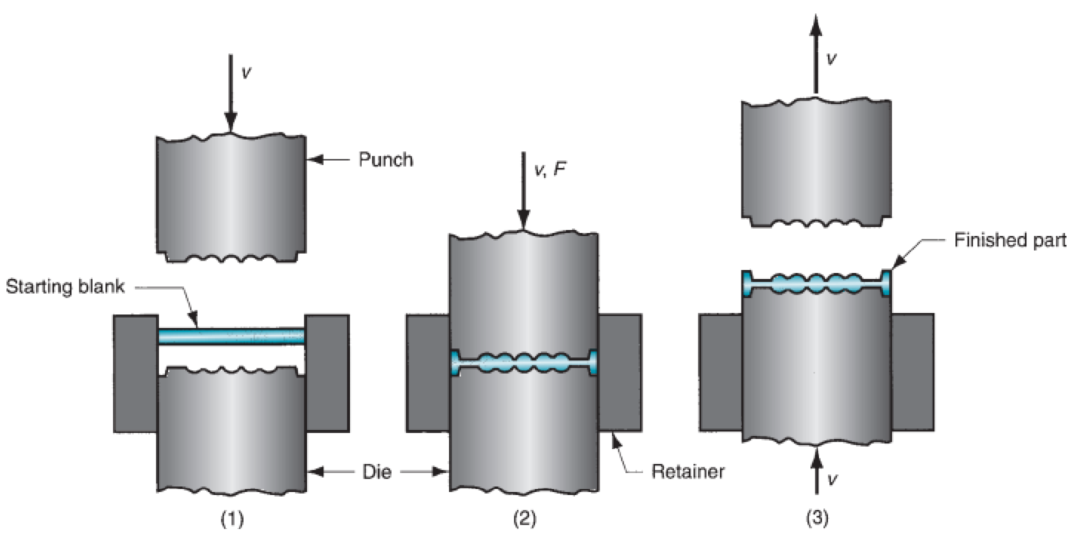

Figure 7.10 Coining operation: (1) start of cycle, (2) compression stroke, and (3) ejection of finished part.

7.6. Forging Hammers, Presses, and Dies

Equipment used in forging consists of forging machines, classified as hammers or presses, and forging dies, which are the special tooling used in these machines. In addition, auxiliary equipment is needed, such as furnaces to heat the work, mechanical devices to load and unload the work, and trimming stations to cut away the flash in impression-die forging.

- **Forging Hammers** Forging hammers operate by applying an impact loading against the work. The term drop hammer is often used for these machines, owing to the means of delivering impact energy (see Figures 7.11). Drop hammers are most frequently used for impression-die forging. The upper portion of the forging die is attached to the ram, and the lower portion is attached to the anvil. I n the operation, the work is placed on the lower die, and the ram is lifted and then dropped. When the upper die strikes the work, the impact energy causes the part to assume the form of the die cavity. Several blow s of the hammer are often required to achieve the desired change in shape. Drop hammers can be classified as gravity drop hammers and power drop hammers. ***Gravity drop hammer*** s achieves their energy by the falling weight of a heavy ram. The force of the blow is determined by the height of the drop and the weight of the ram. ***Power drop hammers*** accelerate the ram by pressurized air or steam. One of the dis ad vantages of drop hammers is that a large amount of the impact energy is transmitted through the anvil and into the floor of the building.

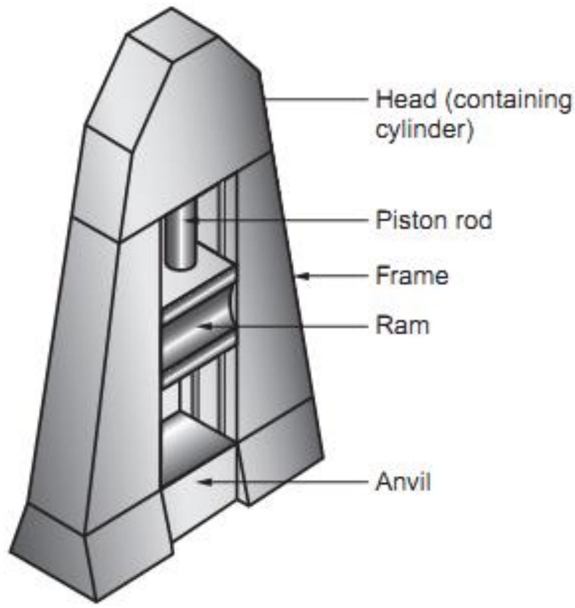

Figure 7.11 Diagram showing details of a drop hammer for impression-die forging.

- **Forging Presses** Presses apply gradual pressure, rather than sudden impact, to accomplish the forging operation. Forging presses include mechanical presses, hydraulic presses, and screw presses. ***Mechanical presses*** operate by means of eccentrics, cranks, or knuckle joints, which convert the rotating motion of a drive motor into the translation motion of the ram. These mechanisms are very similar to those used in stamping presses (Section 20.5.2). Mechanical presses typically achieve very high forces at the bottom of the forging stroke. ***Hydraulic presses*** use a hydraulically driven piston to actuate the ram. Screw presses apply force by a screw mechanism that drives the vertical ram. Both screw drive and hydraulic drive operate a t relatively low ram speeds and can provide a constant force throughout the stroke. These machines are therefore suitable for forging (and other forming) operations that require along stroke.

- **Forging Dies** Proper die design is important in the success of a forging operation. Parts to be forged must be designed based on knowledge of the principles and limitations of this process. Our purpose here is to describe some of the terminology and guidelines used in the design of forgings and forging dies. Design of open dies is generally straightforward because the dies are relatively simple in shape. Our comments apply to impression dies and closed dies. Figure 7.12 defines some of the terminology in an impression die. We indicate some of the principles and limitations that must be considered in the part design or in the selection of forging as the manufacturing process to make the part in the following discussion of forging die terminology:

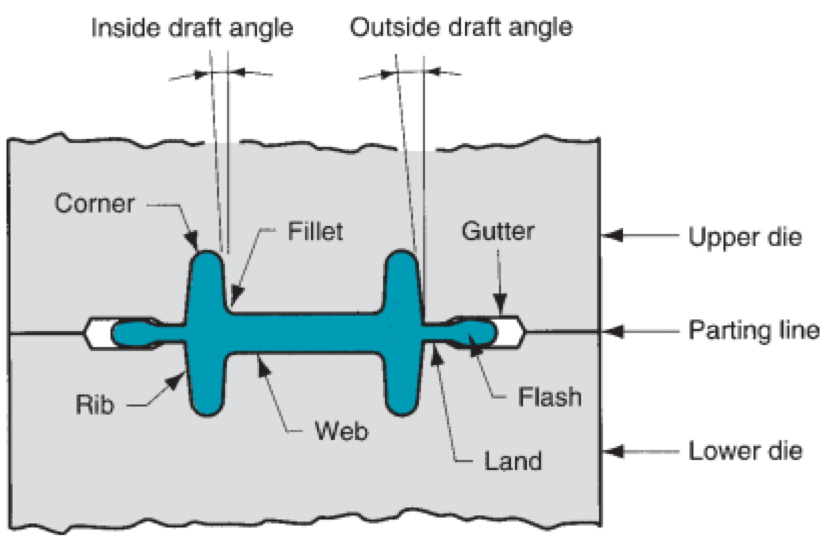

Figure 7.12 Terminology for a conventional impression-die in forging.

- **Parting line:** The parting line is the plane that divides the upper die from the lower die. Called the flash li ne in impression-die forging, it is the plane where the two die halves meet. Its selection by the designer affects grain flow in the part, required load, and flash formation.

- **Draft:** Draft is the amount of taper on the sides of the part required to remove it from the die. The term also applies to the taper on the sides of the die cavity. Typical draft angles are 3° on aluminum and magnesium parts and 5° to 7° on steel parts. Draft angles on precision forgings are near zero.

- **Webs and ribs:** A web is a thin portion of the forging that is parallel to the parting line, while a rib is a thin portion that is perpendicular to the parting line. These part features cause difficulty in metal flow as they become thinner.

- **Fillet and corner radii:** Fillet and corner radii are illustrated in Figure 7.12. Small radii tend to limit metal flow and increase stresses on die surfaces during forging.

- **Flash:** Flash formation plays a critical role in impression-die forging by causing pressure buildup inside the die to promote filling of the cavity. This pressure buildup is controlled by designing a flash land and gutter into the die, as pictured in Figure 7.12. The land determines the surface area along which lateral flow of metal occurs, thereby controlling the pressure increase inside the die. The gutter permits excess metal to escape without causing the forging load to reach extreme values.