FORGING

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. 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, aircraft 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.

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 (1):

1- ***Open-die forging***

2- Impression-die forging.

3- 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. The reader can obtain a good sense of these operations in our video clip on forging.

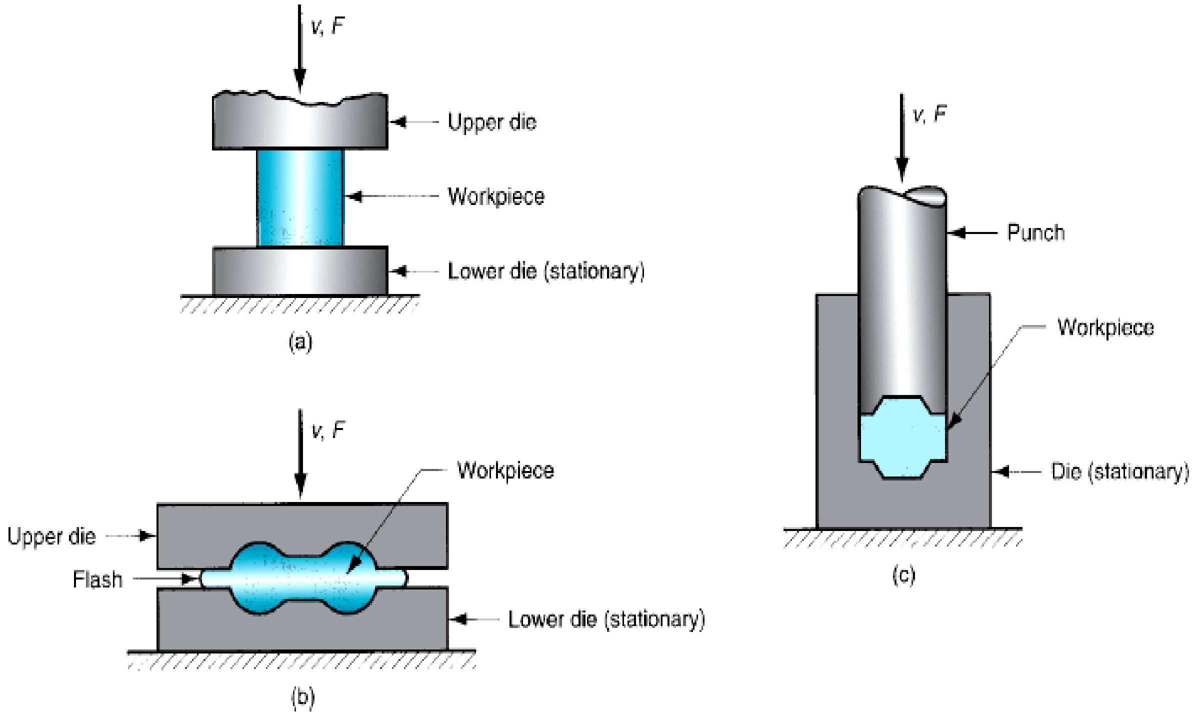


FIGURE (1) Three types of forging operation illustrated by cross-sectional sketches: (a) open-die forging, (b) impression-die forging, and (c) flashless forging.

1- OPEN-DIE FORGING

The simplest case of open-die forging involves compression of a workpiece of cylindrical cross section between two flat dies, much in the manner of a compression test. This forging operation, known as upsetting or upset forging, reduces the height of the work and increases its diameter. In open die forging the dies do not completely cover the workpiece. Instead, there are open spaces that allow various aspects of the workpiece to move from direct hot die contact, and to cooler open areas. In this type of forging, metals are worked above their recrystallization temperatures. Because the process requires repeated changes in workpiece positioning. The workpiece cools during open die forging below its hot-working or recrystallization temperature. It must be reheated before forging can continue.

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 (2). Under these ideal conditions, the true strain experienced by the work during the process can be determined by

$$\epsilon = \ln\frac{h_o}{h} \quad \ldots\ldots\ldots\ldots\ldots\ (1)$$

where h_o: starting height of the work, mm; and h_f: the final height.

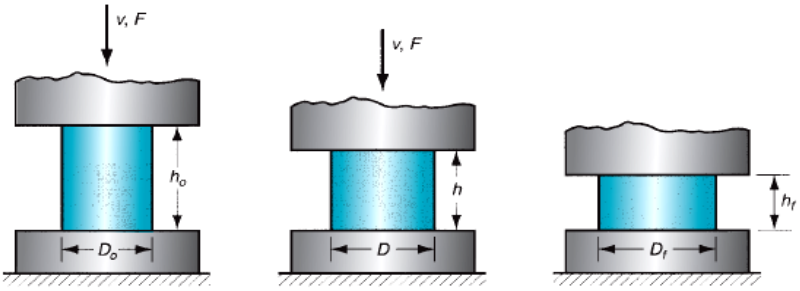


FIGURE (2) Homogeneous deformation of a cylindrical Workpiece under ideal conditions in an open-die forging operation

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:

$F = Y_f A$ …………………. (2)

where F: force (N); A: cross-sectional area of the part,mm^2 ; and Y_f: flow stress

An actual upsetting operation does not occur quite as shown in Figure (2) because friction opposes the flow of work metal at the die surfaces. This creates the barreling effect shown in Figure (3). When performed on a hot Workpiece 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 more readily than the cooler metal at the ends. These effects are more significant as the diameter- to-height ratio of the Workpiece increases, due to the greater contact area at the work–die interface.

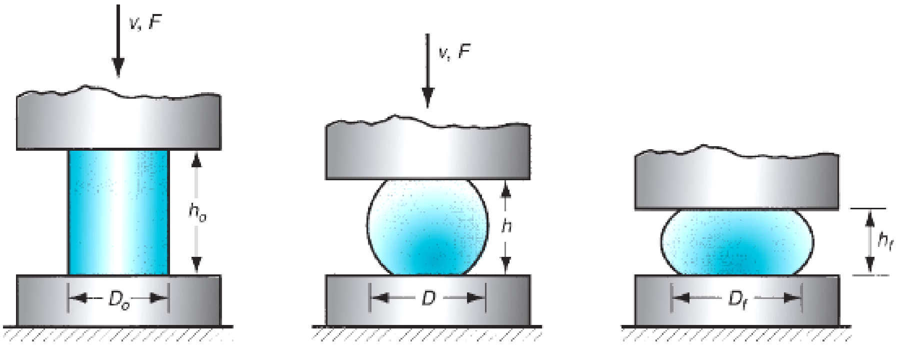


FIGURE (3) Actual deformation of a cylindrical Workpiece in open-die forging, showing pronounced barreling

All of these factors cause the actual upsetting force to be greater than what is predicted by Eq. (2). As an approximation, we can apply a shape factor to Eq. (2) to account for effects of the D/h ratio and friction:

$F = K_f\, Y_f\, A$ ………………….. (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

$$K_f = 1 + \frac{0.4\,\mu D}{h} \quad \ldots\ldots\ldots\ldots\ldots\ (4)$$

where μ: coefficient of friction; D: Workpiece diameter or other dimension representing contact length with die surface, mm ; and h: Workpiece height, mm.

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

Solution: Workpiece volume

$V = 75\pi(50^2/4) = 147{,}262\,mm^3$

At the moment contact is made by the upper die, h=75mm and the force F= 0. At the start of yielding, his 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 = 50mm and area $A = \pi\ (50^2/4) = 1963.5\ \text{mm}^2$. 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 19.12 was developed from the values in this example.

2- *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 (4).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 into 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. In 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 compression 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.

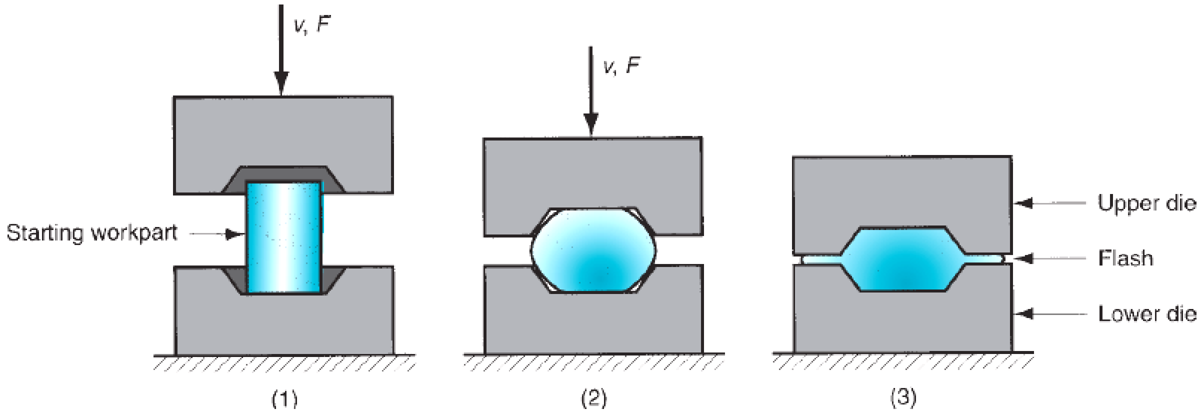


FIGURE (4) Sequence in impression-die forging: (1) just prior to initial contact with raw workpiece, (2) partial compression, and (3) final die closure, causing flash to form in gap between die plates.

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 workpiece 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.

Impression die forging is not capable of making close tolerance objects. Machining is generally required to achieve the accuracies needed. The basic geometry of the part is obtained from the forging process, with subsequent machining done on those portions of the part that require precision finishing like holes, threads etc. ***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 (5).

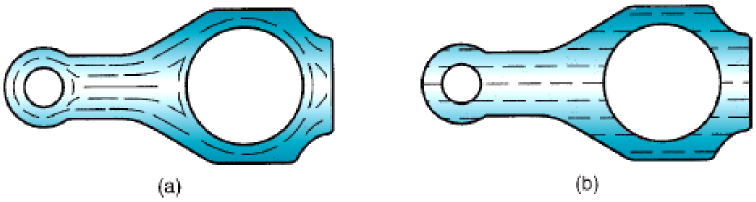


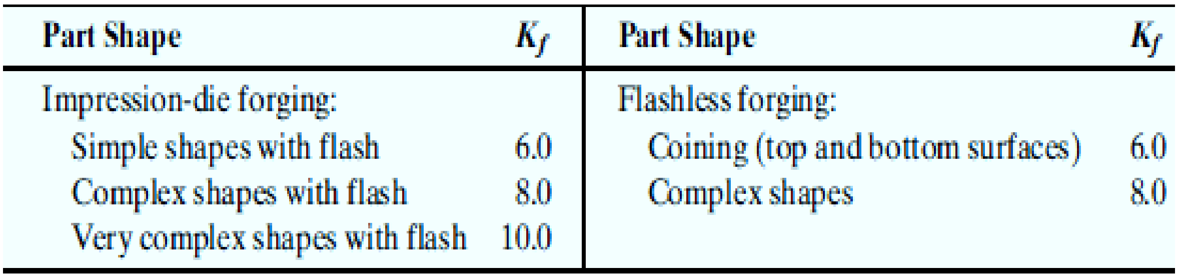
FIGURE (5) Comparison of metal grain flow in a part that is: (a) hot forged with finish machining, and (b) machined complete.

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 Eq. (3) for open-die forging, but its interpretation is slightly different:

$$F = K_f\, Y_f\, A \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; (5)$$

In hot forging, the appropriate value of $\boldsymbol{Y_f}$ 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. $\boldsymbol{K_f}$ in Eq. (5) is a factor intended to account for increases in force required to forge part shapes of various complexities. Table (1) indicates the range of values of $\boldsymbol{K_f}$ for different part geometries. Obviously, the problem of specifying the proper $\boldsymbol{K_f}$ value for a given workpiece limits the accuracy of the force estimate.

TABLE (1). Typical $\boldsymbol{Y_f}$ 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		

3- FLASHLESS FORGING

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 within 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 demands, this process is suitable to make simple and symmetrical part geometries, and to work materials such as aluminum , magnesium and their alloys. The process sequence is illustrated in Figure (6). The term flashless forging is appropriate to identify this 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: Eq. (5) and Table (1).

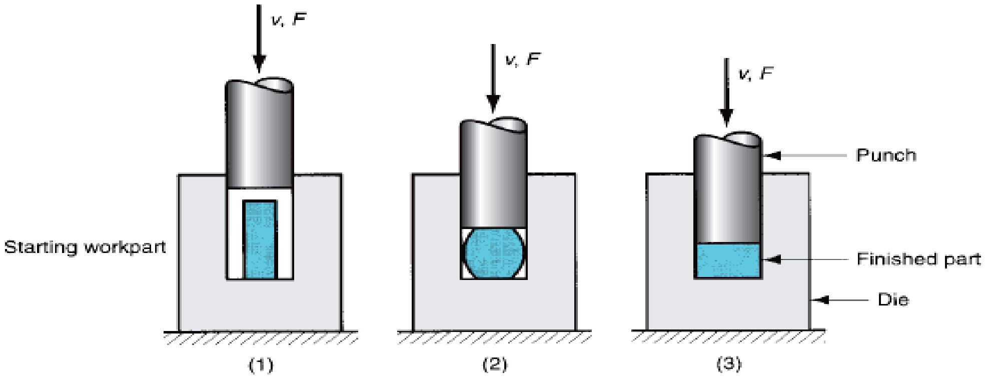


FIGURE (6). Flashless forging: (1) just before initial contact with workpiece, (2) partial compression, and (3) final punch and die closure. Symbols v and F indicate motion (v = velocity) and applied force, respectively.

Trimming: is an operation used to remove flash on the workpart in impression- die forging. In most cases, trimming is accomplished by shearing, as in Figure (7), in which a punch forces the work through a cutting die, the blades for which have the profile of the desired part. Trimming is usually done while the work is still hot, which means that a separate trimming press is included at each forging hammer or press. In cases where the work might be damaged by the cutting process, trimming may be done by alternative methods, such as grinding or sawing.

FIGURE 19.29 Trimming operation (shearing process) to remove the flash after impression-die forging.