7

Metal Forming

Metal forming processes transform simple-geometry billets/blanks into complex-geometry products through the plastic deformation of the metal in open or closed dies. Due to the high costs of the dies, however, these processes are primarily reserved for mass production. Metals to be formed under (normally compressive) stress must be ductile and have low yield strength. These properties can be favorably induced, when necessary, by preheating the billets/blanks prior to their placement in the press. Furthermore, one should note that metal forming processes may take one or a few iterations (i.e., using one or multiple dies) in yielding near net shape desired geometries with no or little scrap.

Metal forming processes may be classified into two primary categories:

1. Massive forming processes (for bulk deformation), where parts undergo large plastic deformation.
2. Sheet-metal forming processes, where (thin-walled) sheets of metal undergo change in overall shape, but not much in their cross sections.

In this chapter, we will first briefly overview several common metal forming processes, but present detailed descriptions for only two of those that are targeted for discrete parts manufacturing (versus continuous production, such as for tubes and pipes): forging and sheet metal forming.

7.1 OVERVIEW OF METAL FORMING

7.1.1 Mechanical Behavior of Metals

Deformation of a solid body can be classified as elastic or plastic: when unloaded, an elastically deformed body always returns to its original shape regardless of history, rate, time, and path of loading; the plastic deformation of a body, on the other hand, depends on all these variables and is subjected to (permanent) loss of original shape when unloaded. Although the theory of elasticity is well established and yields accurate predictions of strain (due to mechanical stress), the theory of plasticity normally yields approximate solutions to plastic deformation problems.

The typical one-dimensional stress–strain curve shown in Fig. 1a for a tension test would normally be also applicable to the compression of ductile metals. As a load is applied on a metal part, it elongates in a linear proportion to the force until the stress level reaches the yield stress value, *Y*. At this critical point, when the load is released, the strain level of the part would be 0.2% or less. At any point before that, the part would completely recover its original shape. As the load is increased beyond the yield stress value, the part undergoes plastic deformation in a uniform-elongation phase until the stress level reaches the ultimate tensile strength value, *UTS*. At any point during this phase, if the load is removed, the part would recover the elastic strain portion of the deformation but permanently maintain the plastic elongation (or shortening in the case of compression) (Fig. 1b).

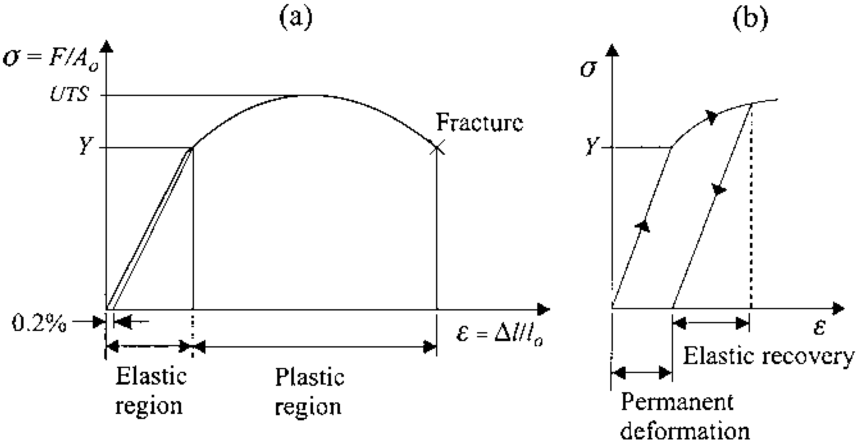


FIGURE 1 (a) Stress–strain curve for tension. (b) Loading-unloading cycle for plastic deformation: F, force; A_o, cross-sectional area; l_o, part's original length; Δl, incremental elongation.

Beyond the *UTS* stress level, the continuing application of load would lead to nonuniform elongation and eventual fracture of the part. In this context, *ductility* is the percentage of plastic deformation that the part undergoes before fracture.

As mentioned above, in metal forming the preference would be to process materials whose ductility is high (and that could be made even higher with increased temperature). Another important factor that we must take note of in metal forming is the rate of deformation (i.e., the amount of strain per unit time). It has been accepted that as the rate of deformation is increased, so would the necessary amount of stress to induce the required strain rate. As the temperature of the part is increased, however, one can obtain higher rates of deformation. Thus one can conclude that increasing temperature raises ductility, lowers yield stress, and thus shortens forming cycle times.

7.1.2 Common Metal-Forming Processes

Forming processes are broadly classified into massive forming and sheet metal processes. The former can be further divided into forging, rolling, extrusion, and drawing, while the latter include processes such as shearing/blanking, bending, and deep drawing. Some of these processes are briefly discussed below as preamble to a more detailed presentation of forging and sheet metal forming processes in Secs. 7.2 and 7.3, respectively. One must note, however, that most parts produced through metal forming could also be (geometrically) fabricated via casting or powder processing. It is the manufacturing engineer's responsibility to choose the most suitable fabrication method to satisfy the numerous constraints at hand, such as mechanical properties, dimensional requirements, and cost.

Forging

Forging is one of the oldest metal forming processes; it can be traced to early civilizations of Egypt, Greece, Persia, China, and Rome, when it was used in the making of weapons, jewellery, and coins. Forging, however, became a mainstream manufacturing process in the 18th century with the development of drop-hammer presses. Today, in closed-die forging, a part can be formed under compressive forces between the two halves of a die, normally in several steps, or in one step (with or without flash) (Fig. 2). The thin flash formed during closed-die forging cools quickly and acts as a barrier to further outward flow of the blank material, thus, forcing it to fill the cavity of the die.

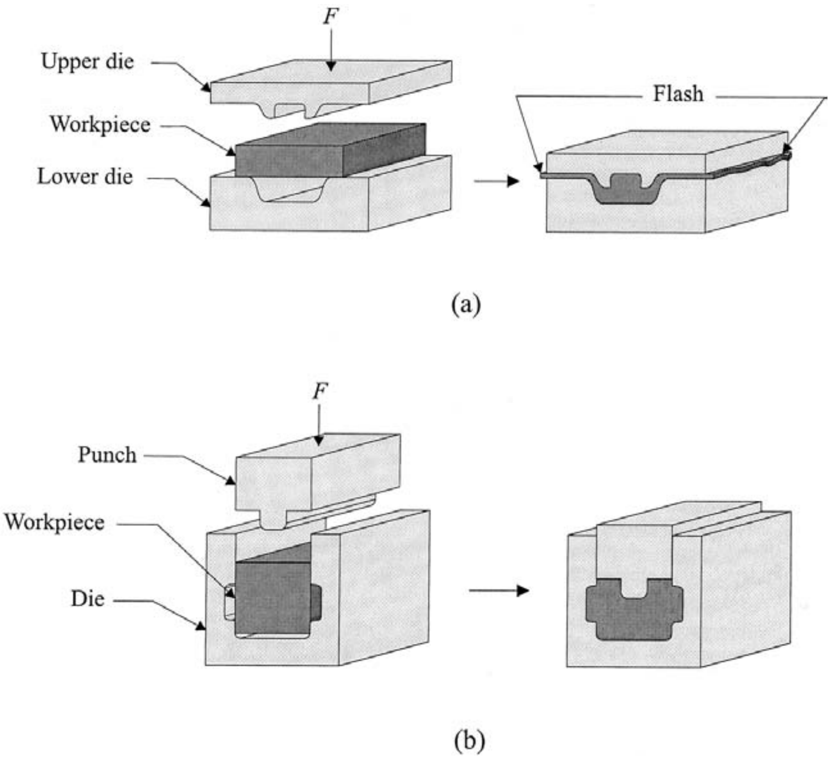


FIGURE 2 Closed die forging (a) with flash; (b) without flash.

Rolling

The rolling of metals can be traced to the 16th and 17th centuries in Europe—rolling of iron bars into sheets. Widespread rolling, however, was only initiated in the late 1700s and early 1800s for the production of railway rails. Today, rolling is considered to be mainly a continuous process targeted for sheet and tube rolling (Figs. 3a, 3b, respectively). Sheet rolling can be a hot or cold forming process for reducing the cross-sectional area of a sheet (or slabs and plates with higher thicknesses than sheets). The workpiece is forced through a pair of rolls repeatedly—each time reducing the thickness further. A rolling process can be utilized in shaping the cross section of a workpiece, such as I-beams or U-channels, or reducing the cross-sectional thickness and/or the diameter of a tube.

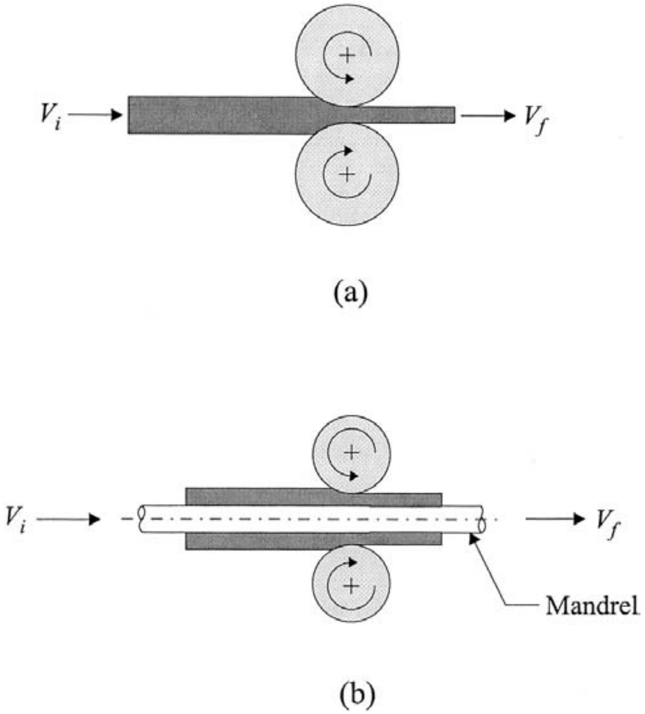


FIGURE 3 (a) Sheet rolling; (b) tube rolling.

Extrusion

The development and use of continuous extrusion can also be traced to Europe in the 1800s for the fabrication of pipes. Today, extrusion is utilized for the fabrication of simple as well complex cross-sectional solid or hollow products. It is based on forcing a heated billet through a die (Fig. 4). In direct extrusion, the product is extruded in the direction of the ram movement. In indirect extrusion, also known as backward or reverse extrusion, the (plastically) deformed product of hollow cross section flows in the opposite direction to the movement of the ram, (solid cross sections can also be obtained when utilizing a hollow ram).

Drawing

Drawing reduces the cross-sectional area of a rod, bar, tube, or wire by pulling the material (in a continuous manner) through a die (Fig. 5), in

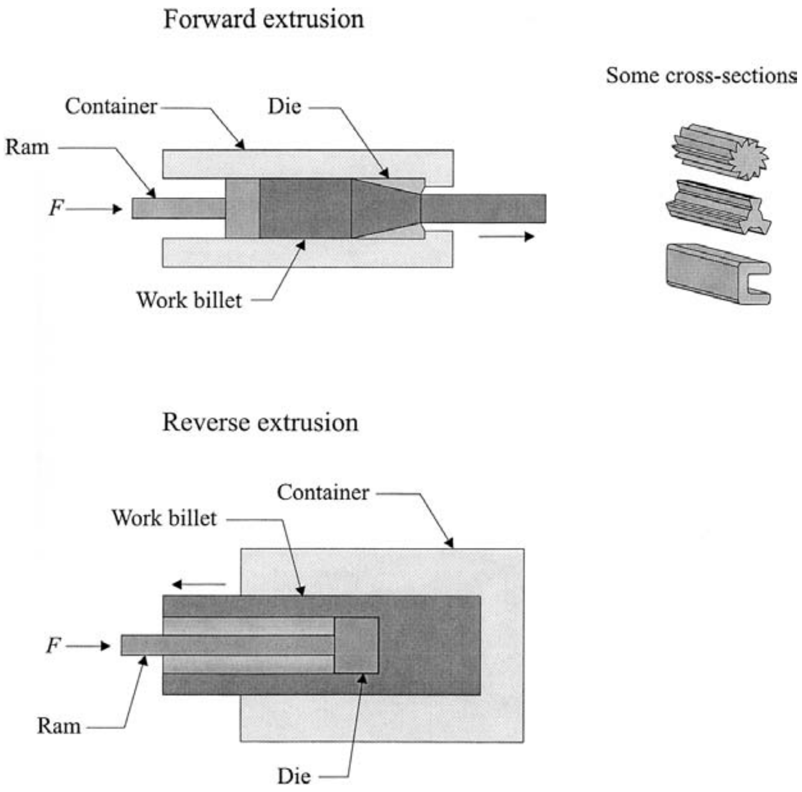


FIGURE 4 Extrusion.

contrast to the pushing action in extrusion. This process is normally a cold-working operation and can be carried out with a pair of undriven rolls instead of a die.

Sheet Metal Forming

Sheet metal forming refers to the forming or cutting/shearing of thin-walled sheets into discrete parts, including car body components and beverage cans. Little or no change in cross-sectional area is expected. In numerous cases, the amounts of elastic and plastic deformations are comparable, leaving the engineer to deal with "springback" effects. Commonly, sheet metal forming is performed on presses through the use of dies.

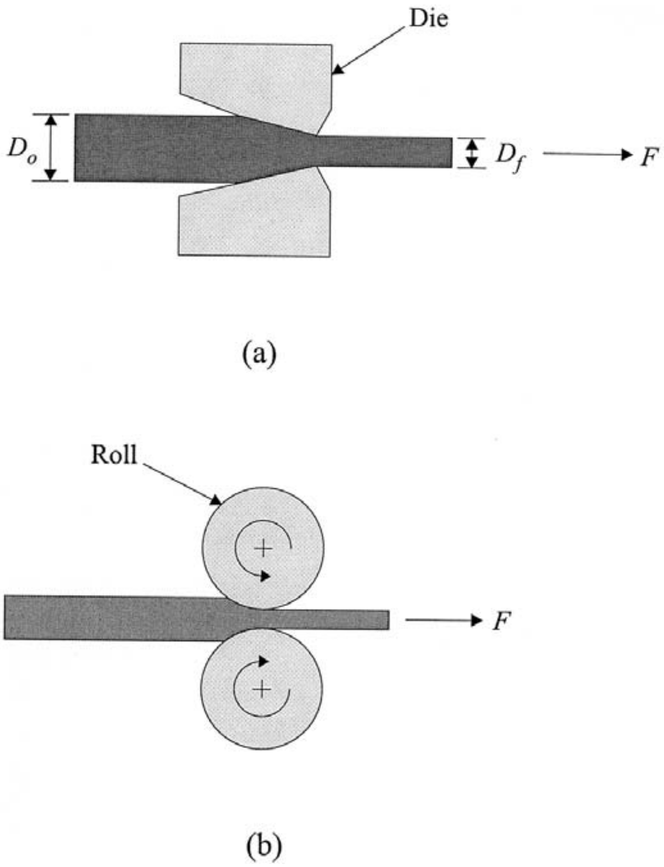


FIGURE 5 (a) Die drawing; (b) roll drawing.

7.1.3 Materials for Metal Forming

Formability of materials depends on the following factors: process temperature, rate of deformation, stress and strain history, and thermal/physical/mechanical properties of the material (including composition and microstructure). Ductile materials are ideal for forming. Brittle materials must be powder processed (Chap. 6). A representative list of materials suitable for metal forming processes is

Forging: Aluminum alloys, copper alloys, carbon and alloy steels, titanium alloys, tungsten alloys, stainless steel alloys, and nickel alloys.

Rolling: Aluminum alloys, copper alloys, carbon and alloy steels, titanium alloys, and nickel alloys.

Extrusion: Aluminum alloys, copper alloys, magnesium alloys, zinc alloys, lead alloys, titanium alloys, molybdenum alloys, and tungsten alloys.

Drawing: Aluminum alloys, copper alloys, alloy steels, stainless steels, cobalt alloys, chromium alloys, and titanium alloys.

Sheet metal forming: Low-carbon steels, aluminum alloys, titanium alloys, and copper alloys.

7.2 FORGING

Forging is a process in which metal billets are plastically deformed by compressive forces, normally within closed dies. Today, forging is the most common metal forming process for the fabrication of discrete solid (versus thin-walled) parts: connecting rods for the automotive industry, shafts for aircraft turbines, and gears for a variety of transportation equipment. Forged parts, small or large, although formed into net shape geometries, generally, require additional finishing operations for dimensional as well as mechanical properties improvements. Forging operations can be performed either cold or hot. Cold forging at room temperature requires greater forces than hot forging but yields much better dimensional accuracy and surface finish.

7.2.1 Forging Techniques

There are a large number of forging techniques, including open-die forging. Only four of these will be detailed below.

Closed Die Forging

In closed die forging, also known as impression-die forging, the billet acquires the shape of the cavity formed between the two halves of the die when closed under pressure (Fig. 2). The process is commonly carried out in several steps to reduce significantly the amount of force at each formation step and to minimize the possibility of defects as well as the amount of waste material (flash). The division of the overall objective into a smaller number of tasks is part geometry and material dependent. The design of the intermediate preform dies is a nontrivial task—it will be briefly addressed in Sec. 7.2.2.

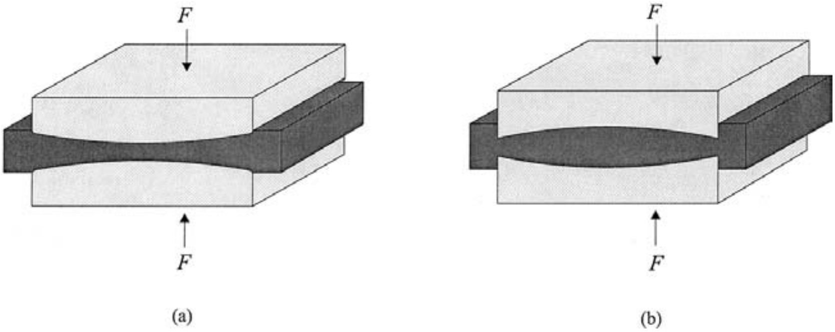


FIGURE 6 (a) Fullering; (b) edging.

The first task in closed die forging is the careful preparation of the billet/blank: it may be cut from an extruded bar or received directly from a casting process; subsequently, it is subjected to a preshaping process, normally through open die forging, when the material is distributed to different regions of the billet. Fullering distributes material away, while edging gathers it into an area/region of interest (Fig. 6). An important preparatory step in the forging process is lubrication through spraying (1) of the die walls with molybdenum disulfide or other lubricants for hot processes and (2) of the blank's surface with mineral oils for cold processes.

Built-in automation is widely utilized in closed die forging for the transfer of preforms from one cavity into another, commonly within the same die/press, as well as for the spraying of the die walls with lubricants. External industrial robotic manipulators have also been used in the placement of billets/blanks into induction furnaces for their rapid heating and their subsequent removal and placement into hot forging presses. Except in cases of flashless forging (Fig. 2b), these manipulators can also transport the parts into flash trimming and other finishing machines.

Extrusion Forging

Extrusion forging is normally a cold process and can be performed as forward or backward extrusion. In forward extrusion, a billet placed in a stationary die is forced forward through a die to form a hollow, thin-walled object, such as stepped or tapered diameter shafts used in bicycles (Fig. 7a).

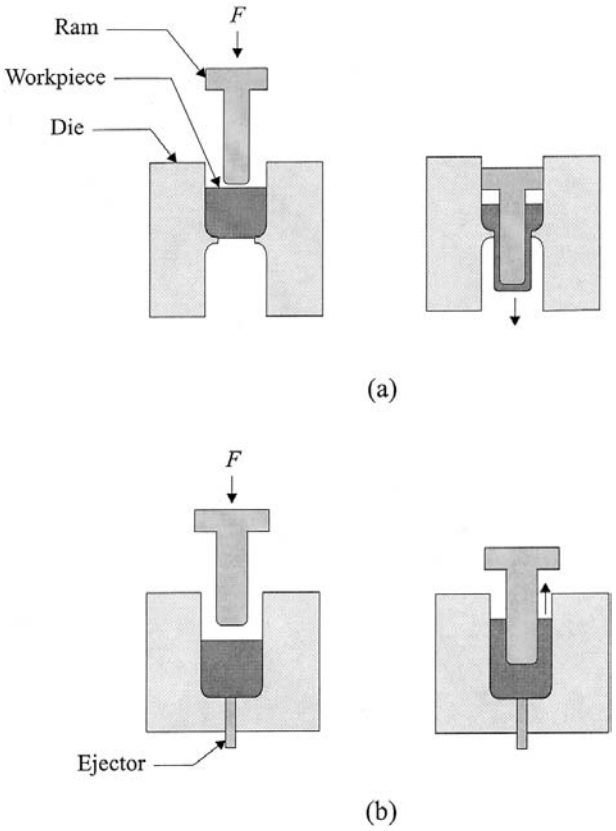


FIGURE 7 (a) Forward extrusion; (b) reverse extrusion forging.

In backward extrusion, also referred to as impact extrusion, a moving punch extrudes backward a billet placed in a (closed) cavity, also for the production of hollow, thin-walled objects (Fig. 7b).

Orbital Forging

In orbital forging, a metal blank is placed in the lower half of a die and deformed incrementally by the rotating upper half of the die. Synchronous to this rotation, the part can be raised upward by a piston that is part of the lower half of the die (Fig. 8). This process is also referred to as rotary forging and can be performed as a hot or cold operation. Bearing rings, bearing end covers, bevel gears, and various other disc-shaped and conical parts can be rotary forged.

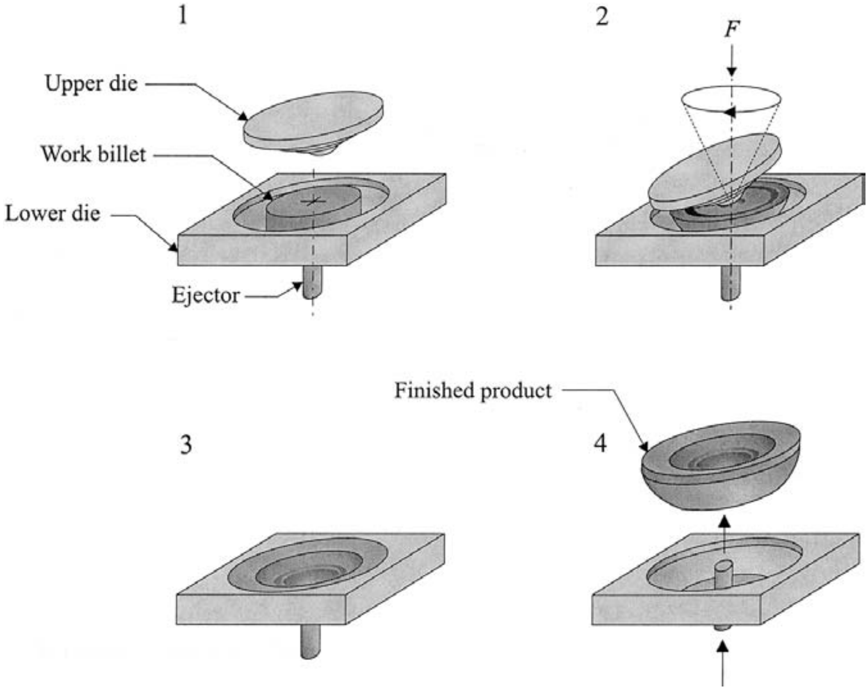


FIGURE 8 Orbital forging.

Roll Forging

Roll forging forms a metal blank into a desired shape by feeding it through a pair of rolls with shaped grooves (Fig. 9). The rolls are in operation for only a portion of their rotational cycle. This hot-forming process is termed forging although it does not employ a moving hammer/punch. It can be utilized for the production of long and thin parts, including tapered shafts, leaf springs, and, occasionally, drill bits (when the blank is also rotated with respect to the rolls as it advances between them). In a process similar to roll forging, alloyed steel gears can be manufactured by forming gear teeth on a hot blank fed between two toothed-die rolls (wheels).

7.2.2 Forgeability and Design for Forging

Forging produces parts of high strength-to-weight ratio, toughness, and resistance to fatigue failure. Metal flow within a die is affected by the resistance of the material to flow (i.e., forgeability), the friction and heat

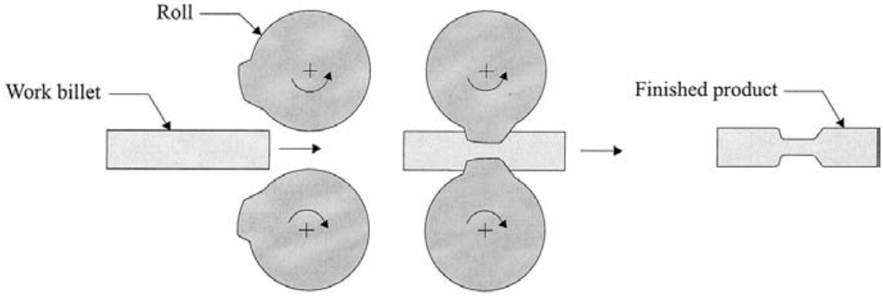


FIGURE 9 Roll forging.

transfer phenomena at the die/material interface, and the geometry of the part. Forgeability, in turn, is influenced by the metallurgical characteristics of the material and the actual process parameters, such as forming temperature and strain rates. Aluminum alloys are the least difficult to forge, normally at a temperature range of 400 to 550°C. Steels are more difficult to forge (at 1100 to 1250°C). Tungsten alloys are considered to be the most difficult materials to forge (at 1200 to 1300°C).

A forging process must ensure adequate flow of the material in the die cavity, thus preventing the occurrence of external and/or internal defects. As mentioned above, metal flow is affected by part geometry. Spherical and block like geometries are the easiest to forge in closed dies. Parts with long, thin sections or projections are more difficult to forge due to their high surface-area-to-volume ratios (i.e., increased friction during metal flow and severe temperature gradients during cooling). Wall thicknesses should be more than 1 mm for steel and more than 0.1 mm for aluminum. One must also make allowances for future machining operations and, most importantly, for material overflow.

As discussed above, complex part geometries require several preforming operations to achieve gradual metal flow. Thus the design of the intermediate die cavity geometries is one of the most important tasks in closed die forging. Although often referred to as art, the generation of the preform cavity geometries (i.e., process planning) would benefit from the use of computer-aided engineering (CAE) tools (such as finite element modeling) for metal flow analysis, as well as from the use of group technology (GT) tools for accessing past process plans developed for similar part geometries (Chaps. 3, 5).

One of the objectives of preforming is to minimize the material loss during forging—the flash. However, it is well established that forging loads increase as flash thickness decreases. Thus, one must optimally design for suitable flash loss while trying to minimize forging loads.

Other factors that affect closed die forging include

Draft angles: 2° to 4° draft angles could facilitate the removal of parts from die cavities when utilizing mechanical ejectors. These may have to be increased to 7 to 10° for manual removals.

Corner radii: Sharp corners must be avoided for increased ease of metal flow.

Parting line: The position of parting lines affects the ease with which billets can be placed in die cavities and the subsequent removal of the preforms and finished parts. It also impacts on the grain flow within the part, and thus on its mechanical properties.

7.2.3 Forging Machines

Presses and hammers are used in the forging of discrete parts. They are primarily chosen according to the part geometry and material as well as production rates. Hydraulic mechanical, and screw presses are used for both hot and cold forging, while hammers are mostly used in hot forging.

Hydraulic Presses

Hydraulic presses can be configured as vertical or horizontal machines and can operate at rates of up to 1.5 to 2.0 million parts per year. Although they operate at much lower speeds than do mechanical presses, the ram speed profile can be programmed to vary during the stroke cycle.

Mechanical Presses

Mechanical presses can also be configured as vertical or horizontal. The driver system (crank or eccentric) is based on a slider–crank mechanism (Fig. 10). Since the ram is fitted with substantial guides and since the press is a constant stroke machine, mechanical presses yield better dimensional accuracy than do hammers. Knuckle joint (mechanical) presses that can produce larger loads for short stroke lengths are often used for cold coining operations. The primary power sources for large mechanical presses are DC motors.

Screw Presses

Screw presses utilize a friction, gear transmission, electric or hydraulic drive to accelerate a flywheel–screw subassembly for a vertical stroke (Fig. 10). In the most common friction drive press, two driving disks (in continuous

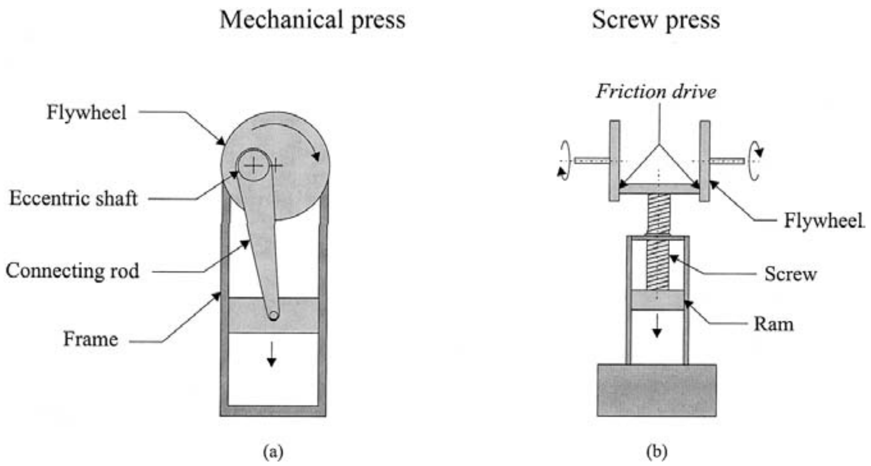


FIGURE 10 (a) Mechanical forging press; (b) screw press.

motion) are utilized to engage a flywheel through friction (one disk at a time, for upward and downward motion). The flywheel, in turn, accelerates the screw attached to it in a downward/upward motion, where maximum speed is achieved at the end of the stroke.

Hammers

A hammer press is a low-cost forging machine that transfers the potential energy of an elevated hammer (ram) into kinetic energy that is subsequently dissipated (mainly) by the plastic deformation of the part. The two most common configurations are the gravity-drop hammer and the power-drop hammer (Fig. 11). As the name implies, the former utilizes only gravitational acceleration to build up the forging energy. The latter type supplements this energy through the utilization of a complementary power source—most commonly hydraulic—for increased vertical acceleration.

The selection of a suitable forging machine for the task at hand is influenced by several factors: part material and geometry and desired rate of deformation (i.e., strain rate). Hydraulic presses can achieve a stroke speed of up to 0.3 m/s and apply a force of typically up to 500 MN in closed die forging. Mechanical presses can achieve a stroke speed of up to 1.5 m/s and apply a force of typically up to 100 MN. (A power-drop hammer, in contrast, can achieve a stroke speed of up to 9 m/s.) Presses are normally preferred for more ductile materials than those for hammers (e.g., aluminum versus steel).

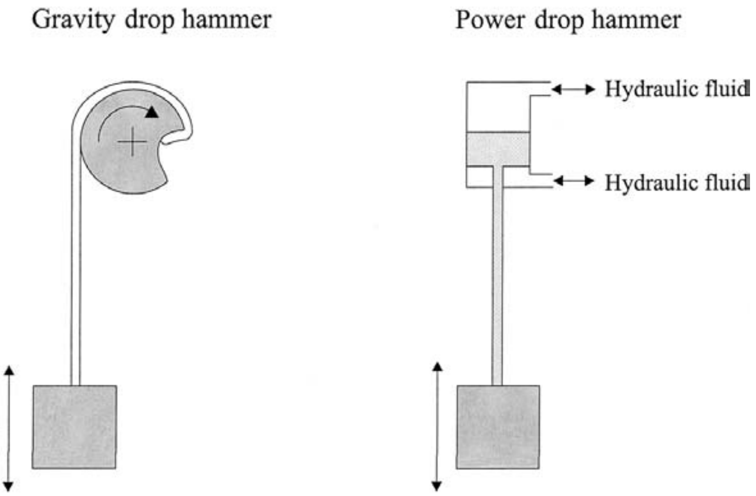


FIGURE 11 Hammers for forging.

7.3 SHEET METAL FORMING

In sheet metal forming, a sheet blank is deformed, normally, into a three-dimensional object—the deformation usually changes the shape of the part but not its cross-sectional thickness. Among the numerous sheet metal forming operations, only a selective few that are most pertinent to discrete manufacturing will be detailed in this section. They are deep drawing, blanking/stamping, and bending. Products manufactured through these processes include desks and cabinets, appliances, car bodies, aircraft fuselages, and a variety of cans.

7.3.1 Sheet Metal Forming Processes

Blanking

The terms blanking and stamping have been used interchangeably to describe the shearing of planar blanks out of a metal sheet, mostly for their subsequent forming into three-dimensional objects via other forming operations. Typically, the sheet metal is secured and a punch/die combination is utilized to shear a desired cross-sectional geometry. Although the outcome of shearing is a blank with not-so-smooth edges, if necessary a fine blanking operation, developed in the 1960s, can be utilized to obtain smooth and vertical edges, for products that will not be further plastically deformed.

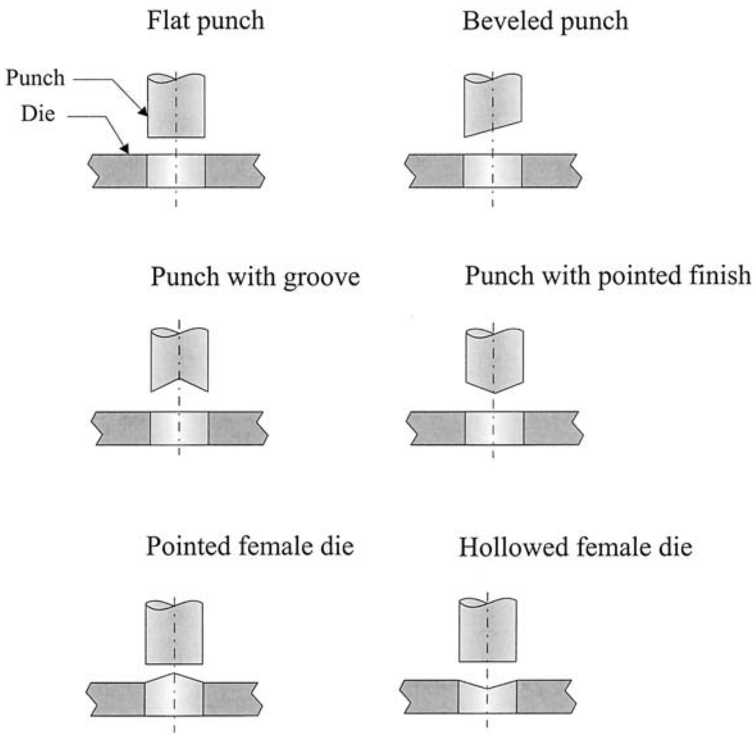


FIGURE 12 Blanking punch die configurations.

As shown in Fig. 12, the blanking force can be reduced if a beveled punch with an oblique shearing move or other nonflat punches are utilized. However, if the part is intended to be used with no further forming, the punch should be either flat or symmetical (with a groove, pointed end, or hollow face). One must also determine a suitable gap between the punch and the die (typically 2 to 8% of the sheet's thickness) for smooth fracture (shearing). In fine blanking, where the sheet is held in place by a pressure pad (with V-shaped projections that penetrate the sheet metal for a better grip), the gap is only about 1%. (Lower clearances are normally reserved for thin and ductile metals.)

Deep Drawing

Deep drawing is a metal forming process targeted for the production of thin-walled cup/can shape objects through a combined compression–tension operation. As shown in Fig. 13, a blank is forced into a die cavity by a punch and assumes the shape of the punch while being held by the blank

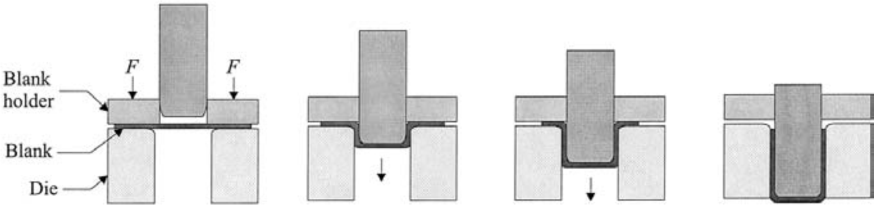


FIGURE 13 Deep drawing.

holder. The process normally maintains the thickness of the sheet metal and can be used for shallow or deep parts. In an alternative configuration, reverse drawing, the location of the punch can be reversed, leading to an upward motion (against gravity).

In certain applications, parts can be deep-drawn in several steps—redrawing. At each step, the cup becomes longer (deeper) and its diameter is reduced. However, if the wall thickness needs to be reduced as well, an ironing operation is implemented. In this process, as the part is redrawn, it is forced through an ironing ring (like an extra die) placed inside the cavity (Fig. 14). Ironing is the preferred operation for the fabrication of beverage cans.

In order to achieve production efficiency, it has been proposed that multiple dies can be vertically aligned in a tandem configuration, thus allowing greater reductions in wall thicknesses in a single stroke. However, due to misalignment problems and the necessary long stroke, an alternative arrangement was developed, a stepped die. In this single-die design, successive reductions can be achieved within a shorter stroke.

Bending

Bending is one of the simplest, yet widely used, metal forming operations. Bending of large metal sheet plates into auto body or appliance body parts

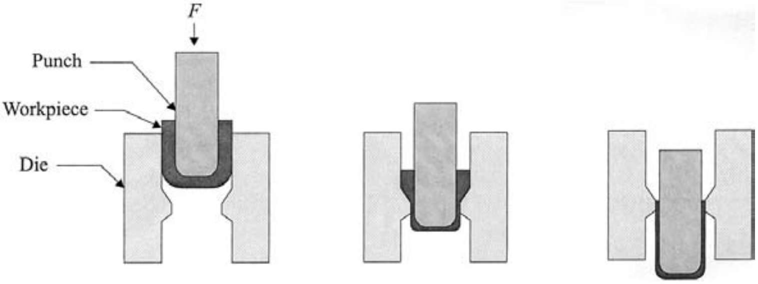


FIGURE 14 Ironing.

are achieved in mass production presses. The operation involves the forcing of a plate (or parts of it) into simple die cavities (or against a wall) by a punch. Since elastic and plastic deformations are typically of the same order of magnitude, the resultant springback effect must be compensated for by overbending the plate. An alternative to overbending would be to implement localized plastic deformations for increased resistance to the springback effect.

7.3.2 Formability and Design for Sheet Metal Forming

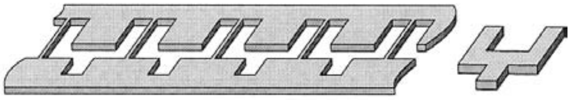
Although sheet metal forming operations may seem to be simple techniques, their analysis is complex owing to the possibility of the presence of several failure mechanisms. Despite the existence of empirically determined "formability" curves for different materials, users are always advised to utilize CAE tools for stress analysis. Formability has been formally defined as the ability of the sheet metal to undergo the desired plastic deformation without failure. In deep drawing, for example, failure or defects can occur owing to nonuniform thinning of the cup. Tearing can occur at the bottom of the cup or wrinkling can result at the flange of the cup. The former can be avoided by allowing strain hardening to occur at preferred rates. Wrinkling, on the other hand, can be controlled by applying suitable clamping forces.

As implicitly discussed above, the properties of the blank material influence formability in addition to the process parameters. Alloyed steels, copper alloys (including bronze), and some aluminum alloys are considered to have excellent formability characteristics because of their high strain hardening capabilities. Steels are commonly used in the automotive industry (body parts, bumpers, shock absorbers, exhaust systems, etc.) and the home appliance industry, copper alloys are used for a variety of small finished parts (ballpoint pen cartridges, zip fasteners, screws, etc.) and aluminum alloys are used in the automotive industry, the aircraft industry, and even in the shipbuilding industry. Some titanium alloys have also been sheet formed into parts for the aircraft and aerospace industries.

Layout Planning in Blanking

Optimal positioning of blanks on a strip or a plate can significantly reduce scrap and therefore result in cost savings (minimizing material to be recycled) (Fig. 15). The ultimate solution would naturally be having zero scrap (Fig. 16). One could also have different shapes mixed on a single strip, for better utilization. Overall, the problem is a classical mathematical optimization problem, where the variables are the position and orientation of the blanks on the strip, and the objective function to be minimized is the surface area of the leftover scrap. (An additional variable set could include

Poor configuration



Better configuration

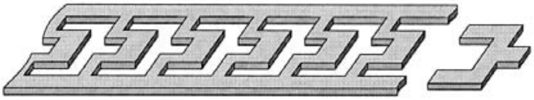


FIGURE 15 Optimal part configuration on a strip.

the outer dimensions of the strip or the plate—for example, if a single row of circular blanks yields 40% waste, by increasing the number of rows to 6 and packing the circles, we could reduce the waste percentage to 25%.)

7.3.3 Dies and Presses for Sheet Metal Forming

As with forging, sheet metal forming may require several steps to obtain the exact shape of the product: the dies must be designed accordingly, and presses should be selected for optimal production. Also, as with forging, manufacturers may decide to combine several preforming cavities (or operations) into a single die (or a single forming station).

Large sheet metal parts (as those found in the automotive industry) are almost always manufactured using single-cavity dies installed in large presses and transferred (sequentially) from one station to another using conveyors or large robotic manipulators. For smaller parts, several single dies can be mounted on a common base plate at one press station, where parts are moved from one die to another (within the same station) automatically.

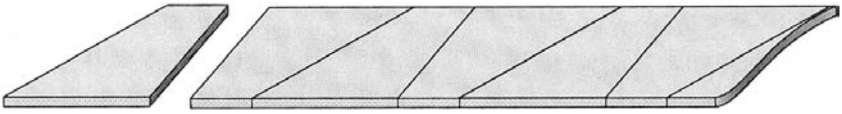


FIGURE 16 No-scrap production.

In stamping, "progressive" dies can be used to blank a part in several stages—i.e., each punch performs one of the many blanking operations needed on one part. The strip on which the part is mounted (or is part of) progresses forward after every blanking operation and finally removed (sheared off) from the strip after the last blanking operation.

Today, manufacturers can decide on choosing dedicated presses for their specific product at hand or choose universal presses that can do both stamping and forming (for small-size parts). As described in Sec. 7.2.3, these presses can be either mechanically or hydraulically driven. However, in the mass production of large parts, an engineer must also carefully design a transportation system for the movement of semifinished (preformed) parts from one station to another. These transportation systems can be of the continuous-line type or targeted for the transfer of small batches. In either case, robotic manipulators with magnetic grippers are very widely utilized throughout the sheet metal forming industry for the loading/unloading/transfer of parts. These manipulators could be of the stand-alone type or built in into the press (the dedicated type) and can handle parts weighing above 50 kg each.

As will be discussed below, in addition to the selection of the most suitable dies, presses, and transport devices, manufacturers must also pay special attention to die changing systems. A quick die exchange technique can significantly increase production efficiency.

7.4 QUICK DIE EXCHANGE

Tactical flexibility in manufacturing requires companies to respond to market demand fluctuations in a timely and profitable manner. A key requirement is to have operational flexibility on the factory floor, whereby production models and batch sizes of parts can be varied without disruptions. Group technology was discussed in Chap. 3 as a potential facilitator for the production of families of (similar) parts within (physical or virtual) workcells. Productivity gains can be achieved in such environments by having common setup tools and procedures, so that setup transformation from one part model to another does not require an excessive amount of time.

In this section, we will briefly review the topic of quick die exchange, which is at the heart of productivity improvement through the elimination of waste (i.e., activities that do not add value to the product). In this context, the single-minute exchange of dies (SMED) philosophy proposed by S. Shingo stands out as an excellent starting point. Shingo's SMED approach is a vital part of a comprehensive manufacturing strategy that he has advocated since the early 1950s: stockless production, the minimization of in-process inventories. SMED is a companion to just-in-time (JIT) manufacturing and defect-free production tactics in this quest. Many hundreds of applications of the SMED philosophy around the world have reduced setup times from several hours to a few minutes, especially in environments of metal forming, metal casting, and plastics molding.

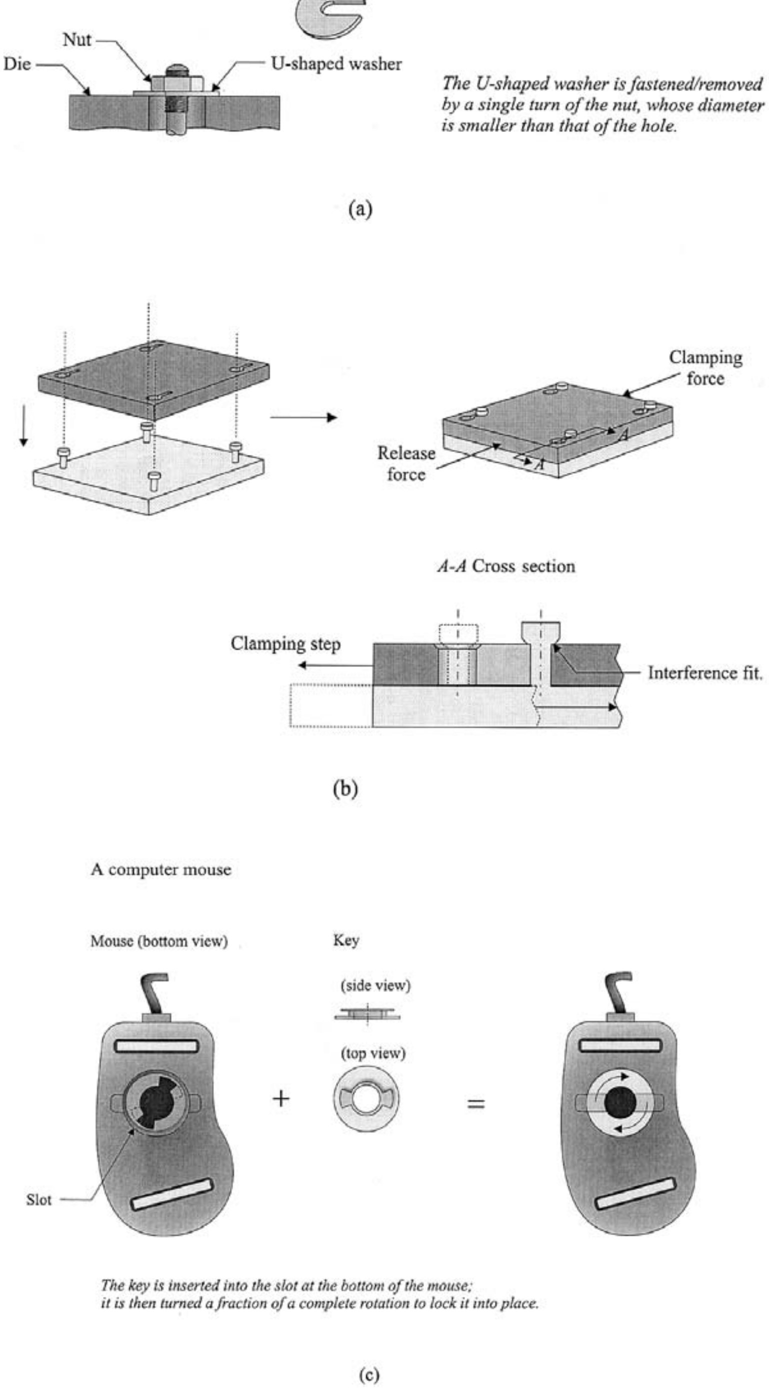
The above-mentioned time savings, via rapid die exchanges, yield increased machine utilization in mixed production environments. This objective is achieved by distinguishing between on-line (internal) and off-line (external) setup activities and increasing efforts to reduce the former activities and thus minimizing the time the machine has to be down. Shingo reports that typically in a setup process on-line activities take up to 70% of the overall die exchange time. Two thirds of this time, in turn, is spent on final adjustments and trial runs. Shingo proposes a two-step approach to waste reduction:

1. Identification and separation of current on-line and off-line setup activities, whereby subsequently maximizing the latter by converting as many of the (current) on-line setup tasks as possible into off-line ones,
2. Reduction of time spent on all on-line and off-line setup activities, with the greater emphasis being on the on-line tasks

Effective a priori preparation of setup tools and their efficient transportation can significantly reduce time spent on on-line activities. For example, mechanization of die mounting through moving bolsters, roller conveyors, revolving die holders, or even through the employment of air cushions will save setup time. Additional operations that were previously carried out on-line, but now are classified as off-line, can also be efficiently carried out to minimize overall setup time. A typical example would be standardization of the functional elements of different dies—modification of die geometry for clamping height standardization, use of centering jigs, and so on.

Reduction of time spent on on-line set-up activities constitutes the primary objective of any productivity improvement attempt. No long list of generic guidelines for this objective exists, so tool and die designers must evaluate every application individually for savings through ingenuity and innovation. Shingo does highlight, however, three generic (common) guidelines:

The use of clamping techniques that miminize the time spent on securing the die in the press should be a priority. Examples include



The U-shaped washer is fastened/removed by a single turn of the nut, whose diameter is smaller than that of the hole.

The key is inserted into the slot at the bottom of the mouse; it is then turned a fraction of a complete rotation to lock it into place.

FIGURE 17 One-turn clamping.

one-turn attachments (where several points of connection are achieved with the turn of one mechanism) (Fig. 17), cam and clamps, spring-loaded pins, etc.

The elimination of as many adjustments as possible through the use of guiding pins, locators, height gages, or even electronic indicators/sensors.

The concurrent (versus sequential) implementation of several on-line tasks. Safety issues should be a paramount concern, however, when utilizing multiple operators.

As a complementary point to the above discussion, the reader must be aware that the frequency of exchanging dies is a direct function of total (on- and off-line) time spent of the setup. Although a die can be removed from a press and replaced by a different one within minutes, this naturally does not imply that it can be remounted after a short while. Off-line die preparation dictates the length of that time. Thus manufacturing engineers must not neglect the issue of minimizing off-line setup times, even when they have reduced the on-line activities to several minutes and maximized machine up-time.

REVIEW QUESTIONS

1. Is metal forming an elastic or a plastic deformation process? Explain.
2. What is material ductility and how does it affect metal forming?
3. Which typical fabrication processes are utilized in the preparation of billets/blanks for forging?
4. Why is it preferable to have forging carried out in multiple steps?
5. Describe forward and backward extrusion forging, respectively.
6. Why are long and thin part sections difficult to forge?
7. Discuss the flash formation process in forging and define its advantages/disadvantages.
8. Discuss the selection of a suitable forging machine.
9. Describe the fine blanking process.
10. Describe the redrawing and ironing processes as well as the deep drawing process that uses multiple dies in tandem or a stepped die.
11. What is the springback effect in metal bending?
12. Discuss the optimal positioning of blanks on a strip for blanking operations.
13. What are progressive dies in forging as well as in blanking?
14. Discuss the topic quick die exchange. Differentiate between on-line (internal) and off-line (external) setup activities.

DISCUSSION QUESTIONS

1. Forging is normally a multistep process: the final shape of the part is achieved via multiple forming operations in a single die with multiple cavities using one forging machine. The parts in progress are moved forward from one cavity to the next after every cycle of the forging. Discuss methods/technologies that allow users optimally to (process) plan the manufacturing process. That is, minimize cost (or time) of manufacturing, subject to achieving the desired geometric and mechanical properties of the part. Similarly, discuss the load-balancing issue for multi-cavity (progressive) forging dies: that is, optimal balancing of the force and energy requirements for the plastic deformation processes in all the cavities, using computer-aided engineering analysis tools, so that the forging press is better configured.
2. Single-minute exchange of dies (SMED) is a manufacturing strategy developed for allowing the mixed production (e.g., multimodel cars) within the same facility in small batches. The primary objective has always been to minimize the time spent on setting up a process while the machine is idle. This objective has been achieved (1) by converting as many on-line operations as possible to off-line ones (i.e., those that can be carried out while the machine is working on a different batch), and (2) by minimizing the time spent on on-line setup operations. Discuss the effectiveness of using SMED or equivalent strategies in the mass manufacturing of multimodel products, the mass manufacturing of customized products, and the manufacturing of small batches or one-of-a-kind products.
3. During the 20th century, there have been statements and graphical illustrations implying that product variety and batch size remain in conflict in the context of profitable manufacturing. Discuss recent counterarguments that advocate profitable manufacturing of a high variety of products in a mass production environment. Furthermore, elaborate on an effective facility layout that can be used in such environments: job-shop, versus cellular, versus flow-line, versus a totally new approach.
4. Analysis of a production process via computer-aided modeling and simulation can lead to an optimal process plan with significant savings in production time and cost. Discuss the issue of time and resources spent on obtaining an optimal plan and the actual (absolute) savings obtained due to this optimization. For example, spending several hours in planning to reduce production time from 2 minutes to 1 minute. Present your analysis as a comparison of one-of-a-kind production versus mass production.

BIBLIOGRAPHY

Altan, Taylan, Oh, Soo-Ik, Gegel, Harold L. (1983). *Metal Forming: Fundamentals and Applications*. Metals Park, OH: American Society for Metals.

Avitzur, Betzalel (1983). *Handbook of Metal-Forming Processes*. New York: John Wiley.

Blazynski, T. Z. (1989). *Plasticity and Modern Metal-Forming Technology*. London: Elsevier Applied Science.

Carle, D., Blount, G. (1999). The suitability of aluminum as an alternative material for car bodies. *J. of Materials and Design* 20:267–272.

Doyle, Lawrence E., et al (1985). *Manufacturing Processes and Materials for Engineers*. Englewood Cliffs, NJ: Prentice-Hall.

Groover, Mikell P. (1996). *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems*. Upper Saddle River, NJ: Prentice Hall.

Hayashi, H., Nakagawa, T. (Nov. 1994). Recent trends in sheet metals and their formability in manufacturing automotive panels. *J. of Materials Processing Technology* 46(3–4):455–487.

Hosford, William F., Caddell, Robert M. (1993). *Metal Forming: Mechanics and Metallurgy*. Englewood Cliffs, NJ: Prentice Hall.

D. Beadle, John (ed.). (1971). *Metal Forming*. Basingstoke, UK: Macmillan.

Kalpakjian, Serope, Schmid, Steven R. (2000). *Manufacturing Engineering and Technology*. Upper Saddle River, NJ: Prentice Hall.

Kobayashi, Shiro, Oh, Soo-Ik, Altan, Taylan (1989). *Metal Forming and the Finite-Element Method*. New York: Oxford University Press.

Marciniak, Z., Duncan, J. L. (1992). *The Mechanics of Sheet Metal Forming*. London: E. Arnold.

Pearce, Roger (1991). *Sheet Metal Forming*. New York: Hilger.

SAE (2000). *Sheet Metal Forming: Sing Tang 65th Anniversary Volume*. Warrendale, PA: Society of Automotive Engineers.

Schey, John A. (1987). *Introduction to Manufacturing Processes*. New York: McGraw-Hill.

Schuler, GmbH. (1998). *Metal Forming Handbook*. Berlin: Springer-Verlag.

Talbert, Samuel H., Avitzur, Betzalel (1996). *Elementary Mechanics of Plastic Flow in Metal Forming*. New York: John Wiley.

Wagener, H. W. (Dec. 1997). New developments in sheet metal forming: sheet materials, tools and machinery. *J. of Materials Processing Technology* 72(3):342–357.

Wagoner, R. H., Chenot, Jean-Loup (1997). *Fundamentals of Metal Forming*. New York: John Wiley.