Elements of Metallurgy and Engineering Alloys
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CHAPTER 16

Deformation Processing

METALWORKING PROCESSES are commonly classified as either hot working or cold working operations. Primary metalworking processes, such as the bulk deformation processes used to conduct the initial breakdown of cast ingots, are always conducted hot. The term *bulk deformation* implies large amounts of material movement, such as in hot rolling or forging. Secondary processes, which are used to produce the final product shape, are also conducted either hot or cold. Some secondary processes, such as sheet forming, do not involve large amounts of deformation.

Hot working processes are conducted at temperatures above the recrystallization temperature, which is approximately 0.5 T_m. Cold working processes are conducted at or near room temperature, while warm working processes are conducted at intermediate temperatures. Hot working produces a recrystallized grain structure, while the grain structure due to cold working is unrecrystallized and retains the effects of the working operation.

Bulk deformation changes the shape of a workpiece by plastic deformation through the application of compressive forces, as for the typical bulk deformation processes in Fig. 16.1. In addition to shaping the metal, bulk deformation is used to refine the structure that results from solidification. To refine the

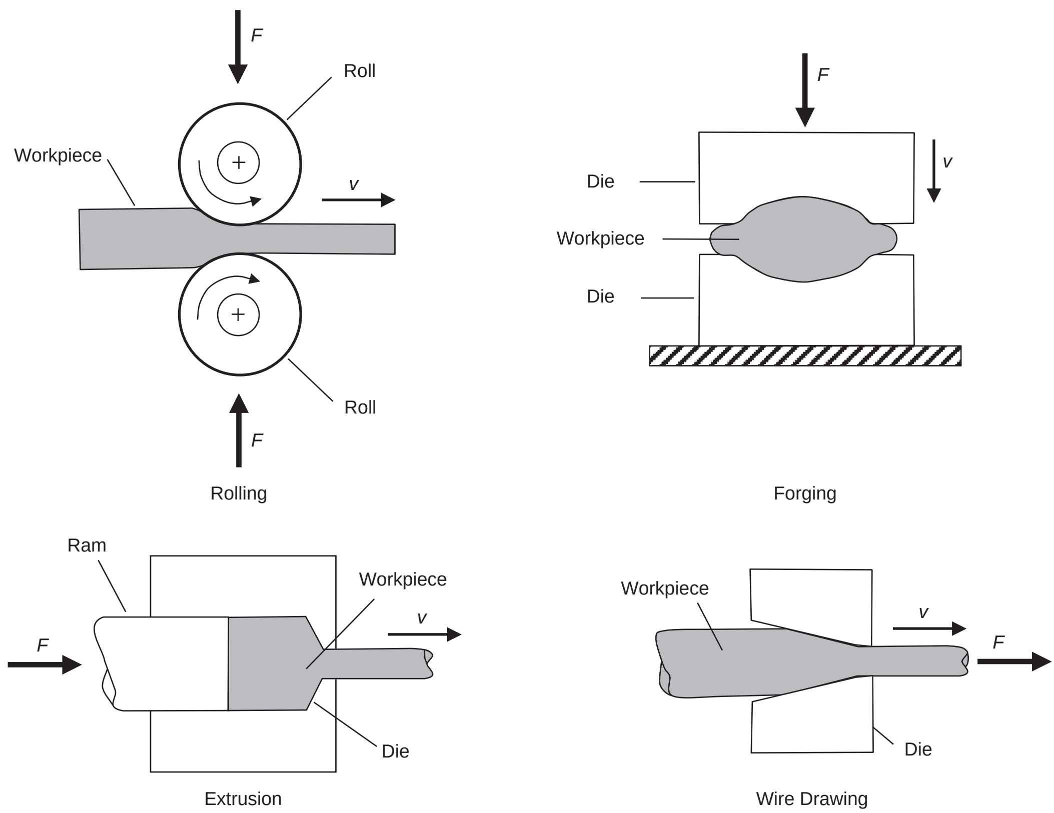

Fig. 16.1 Bulk deformation processes. Source: Ref 1

inhomogeneous structure resulting from solidification, cast ingots and continuously cast slabs and blooms are typically hot worked into intermediate product forms, such as plates, bars, and sheet. Large plastic deformation in combination with heat is very effective in refining the microstructure, breaking up macrosegregations, collapsing and sealing porosity, and refining the grain size. This product may be suitable for its intended application, but in many cases, it provides the starting material for secondary deformation processes such as drawing, hot or cold forging, and sheet metalworking.

Because most processes involve sliding contact between the workpiece and a tool or die, friction affects material flow, die pressures, and the force and energy requirements. In many instances, lubricants are used to minimize friction. Lubricants also reduce die wear, help in providing temperature control, and minimize high-temperature oxidation.

16.1 Hot Working

Hot working normally takes place at approximately 70 to 80% of the absolute melting temperature. During hot working, the strain-hardened and distorted grain structure produced by deformation is rapidly eliminated by the formation of new strain-free grains as a result of recrystallization. Dynamic recrystallization occurs during deformation, while static recrystallization occurs after deformation is complete but while the workpiece is still hot. For processes such as hot rolling, hot extrusion, and hot forging, the time within the deformation zone is usually short, and grain refinement is usually accomplished by static recrystallization after hot working. A high level of hot deformation followed by holding the workpiece at an elevated temperature causes static recovery and recrystallization, resulting in a fine grain size. This may occur during hot rolling (Fig. 16.2) where there is time between roll passes, or after hot forging, where the workpiece slowly cools to room temperature.

Very large deformations are possible in hot working, and since recovery processes keep pace with the deformation, hot working occurs at essentially a constant flow stress (the shear stress required to cause plastic deformation of the metal). Since the flow stress decreases with increasing temperature, metals become more malleable, and less energy is needed to produce a given amount of deformation. However, as the temperature increases, the strength also decreases. Therefore, hot working processes usually involve the use of compressive forces to prevent cracking or failure. Because recovery processes take time, flow stress, σ_f, is a function of strain rate, $\dot{\varepsilon}$:

$$\sigma_f = C\dot{\varepsilon}^m \qquad \text{(Eq 16.1)}$$

where C is the strength coefficient (decreasing with increasing temperature), and m is the strain-rate sensitivity.

A high value of m means that any incipient neck that develops becomes stronger and spreads to neighboring material, allowing more deformation in tension. In some very fine-grained metals, the value of m may reach 0.4 to 0.5 but only at very low strain rates and within a limited temperature range.

Because hot working processes may hold a workpiece at a high temperature for a long time, grain growth can occur. In fact, in an extended hot working process such as ingot breakdown during rolling, a cyclic history of grain

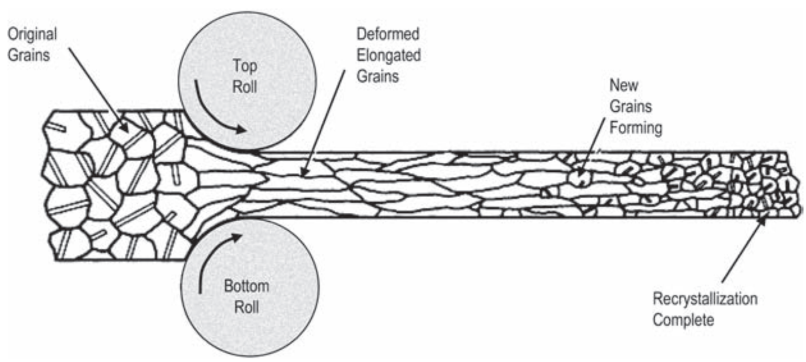

Fig. 16.2 Recrystallization during hot rolling

deformation, recrystallization, and grain growth occurs for each deformation step. The ability to put work into the grains at a level sufficient to cause recrystallization is the reason that fine grains can be developed from a coarse-grained structure by hot working. Thus, hot working processes must balance recovery and recrystallization against grain growth.

At temperatures above the equicohesive temperature, the grain interiors are more resistant to deformation than the grain boundaries, and the grain boundaries can sustain substantial deformation. If a very fine grain size can be achieved and maintained during deformation at a low strain rate, grain-boundary sliding can occur. Creep forming, hot die forging, isothermal forging, and isothermal rolling are processes that rely in part on grain-boundary sliding and other thermally activated deformation mechanisms.

The workability, or the ease with which a metal is shaped by plastic deformation, is lower for cast structures than for wrought structures (Fig. 16.3). Workability is also dependent on grain size and grain structure. When the grain size is relatively large, as in cast structures, workability is lower because cracks can initiate and propagate along grain boundaries. Also, with cast structures, impurities frequently segregate to the center, to the top, or to the surface of the ingot, creating areas of low workability. Because alloying elements are not distributed uniformly, the temperature range over which an ingot structure can be worked is somewhat limited.

The upper limit for hot working is determined by the temperature at which either melting or excessive oxidation occurs. Generally, the maximum working temperature is limited to approximately 40 °C (100 °F) below the

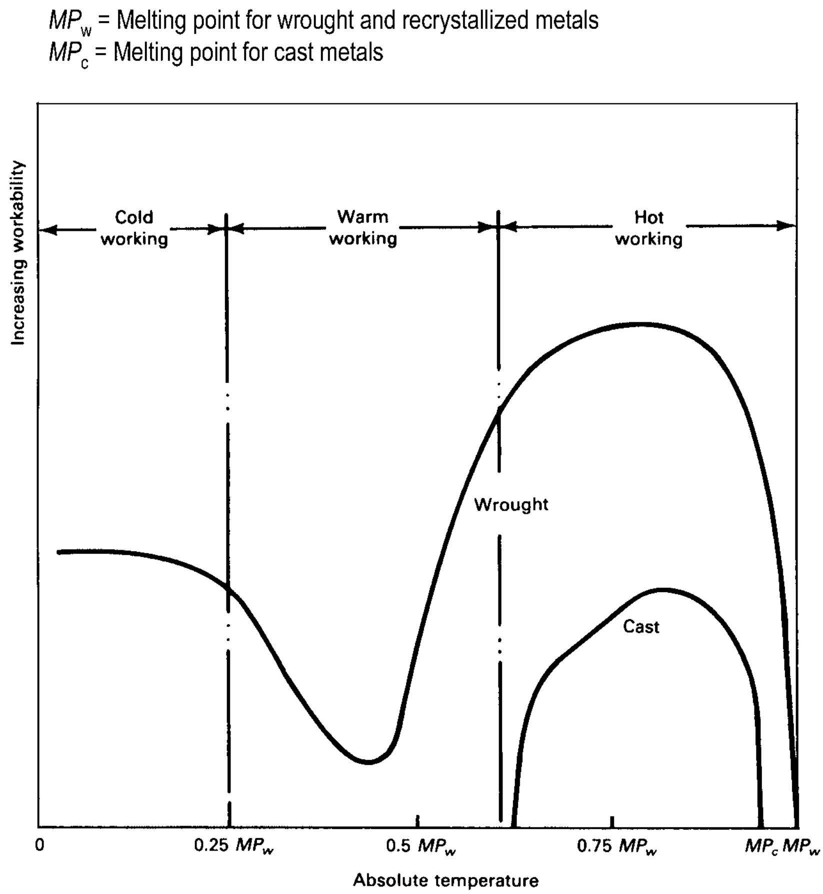

Fig. 16.3 Relative workabilities of wrought and cast metals. Source: Ref 2

melting temperature to prevent the occurrence of hot shortness. The melting point of an alloy in the as-cast condition is usually lower than that of the same alloy in the fine-grain, recrystallized condition, because of chemical inhomogeneities and the presence of low-melting-point compounds that frequently occur at grain boundaries. Deformation at temperatures too close to the melting point of these compounds may lead to grain-boundary cracking when the heat developed by deformation increases the workpiece temperature and produces local melting, a fracture mode called hot shortness. Hot shortness can be prevented by using a sufficiently low deformation rate that allows the heat developed by deformation to be dissipated by the tooling, by using lower working temperatures, or by subjecting the workpiece to a homogenization heat treatment prior to hot working. The intermediate temperature region of low ductility shown in Fig. 16.3 can occur at temperatures that are sufficiently high for grain-boundary sliding to cause grain-boundary cracking but are not high enough for the cracks to be healed by dynamic recrystallization.

The advantages of hot working include:

- Flow stresses are low; hence, forces and power requirements are relatively low. Even very large workpieces can be deformed with equipment of reasonable size.
- Ductility is high, allowing for large deformations.
- Complex part shapes can be produced.

16.2 Cold Working

Cold working produces better surface finishes, can impart higher strengths, and allows thinner products than hot working but requires higher forces. Cold working results in a deformed, unrecrystallized grain structure with the grains elongated in the direction of metal flow. An empirical relationship between flow stress and plastic strain during cold working is:

$$\sigma_f = K\varepsilon^n \quad \text{(Eq 16.2)}$$

where σ_f is the flow stress, K is the strength coefficient (stress when $\varepsilon = 1.0$), ε is the plastic strain, and n is the work-hardening exponent.

A high strength coefficient indicates a high initial resistance to plastic flow, and metals with a high K require large forces for deformation. Work hardening is a measure of how the resistance to plastic flow increases as the metal is deformed. Typically, n has values of 0.1 to 0.5 for cold working, with 0 being a perfectly plastic metal that will not work harden. A high n value allows more tensile deformation before a localized neck develops. A metal with a high work-hardening exponent but a low strength coefficient will achieve a high strength level after a large amount of deformation. Examples include coppers, brasses, and low-carbon steels that are cold worked to produce higher hardness and strength in the formed part. The value of K increases and n decreases in the course of cold working; thus, ductility is reduced and the forces increase. Intermediate process anneals can restore ductility and reduce forces but at an additional cost. Warm working in an intermediate temperature range can combine some of the benefits of hot and cold working. Some values of K and n are given in Table 16.1. For steels, K increases with carbon content, while n generally decreases. Both copper and brass have a much higher work-hardening exponent than steels. Over the range of strain rates at which cold deformation processes are conducted (0.1 to 100/s), the sensitivity to strain rate for most metals is low. Rather, the strain level and the strength coefficient, K, control the flow stress.

During cold working, the grains distort, the grain boundaries align, and a well-defined, fiberlike grain pattern develops. Nonmetallic inclusions can further produce a definite directionality in the microstructure and mechanical properties due to the deformation-induced fibrous microstructure. Extremely deformed microstructures, such as in cold-rolled sheet products, can also develop into aligned crystallographic planes or texture. This results in anisotropic behavior of the deformed material, both in service or during subsequent deformation steps.

Although cold rolling is usually conducted at room temperature, the work of deformation can increase the temperature by as much as 95 to 205 °C (200 to 400 °F). A material subjected to cold rolling strain hardens considerably, and grains become elongated in the direction of major deformation. Dislocation density increases, and when a tension test is performed on the strain-hardened material, a higher stress will be needed to initiate and maintain plastic deformation; that is, the yield stress increases. However, the ductility of the material, as expressed by total elongation and reduction of

Table 16.1 Work-hardening exponents and strength coefficients

Metal	Condition	Work-hardening exponent (n)	Strength coefficient (K) MPa	(ksi)
1100 aluminum	Annealed	0.20	180	26
2024 aluminum	Solution treated and naturally aged	0.16	690	100
6061 aluminum	Annealed	0.20	895	30
6061 aluminum	Solution treated and artificially aged	0.05	405	59
7075 aluminum	Annealed	0.17	400	58
Copper	Annealed	0.54	315	46
70/30 brass	Annealed	0.49	895	130
85/15 brass	Cold rolled	0.34	580	84
0.05% C steel	Annealed	0.26	530	77
4135 steel	Annealed	0.17	1015	147
4135 steel	Cold rolled	0.14	1105	160
4340 steel	Annealed	0.15	640	93
0.6% C steel	Quenched and tempered at 540 °C (1000 °F)	0.10	1570	228
0.6% C steel	Quenched and tempered at 705 °C (1300 °F)	0.19	1225	178
304 stainless steel	Annealed	0.45	1275	185
410 stainless steel	Annealed	0.10	960	139
Cobalt alloy	Heat treated	0.50	2070	300

Source: Ref 3

area, drops because of the higher initial dislocation density.

Advantages of cold working include:

- In the absence of cooling and oxidation, tighter tolerances and better surface finishes are obtained.
- Thinner walls are possible.
- The final properties of the workpiece can be closely controlled, and, if desired, the high strength obtained during cold rolling can be retained, or, if high ductility is needed, grain size can be controlled by annealing.
- Lubrication is, in general, easier.

16.3 Rolling

Rolling is reduction of the cross-sectional area of the metal stock, or the general shaping of the metal products, through the use of the rotating rolls. The rolls rotate to pull and simultaneously squeeze the work between them. After ingot casting, rolling is perhaps the most important metalworking process. More than 90% of all wrought steel, aluminum, and copper produced go through at least one rolling process. Hot rolling helps to break up the as-cast structure and provides a more uniform grain size and a better distribution and size of constituent particles. During hot rolling, the grain structure becomes elongated in the rolling direction, as shown in Fig. 16.4. This grain directionally can have a substantial effect on some of the mechanical properties, especially fracture toughness and corrosion resistance, in which the properties are lowest in the through-the-thickness or short-transverse direction.

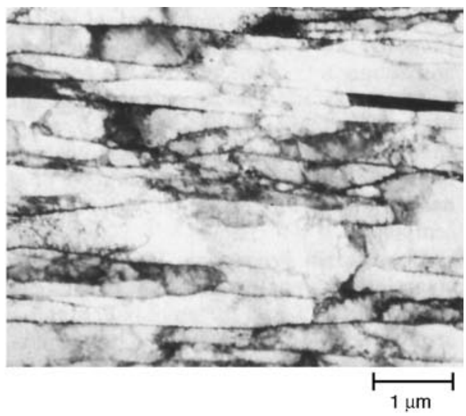

Fig. 16.4 Grain directionality due to rolling of electrolytic iron single crystal. See also Fig. 26.7. Source: Ref 4

The primary objectives of the rolling process are to reduce the cross section of the incoming material while improving its properties and to obtain the desired shape. The process can be carried out hot, warm, or cold, depending on the application and the material involved. During rolling, compression deformation is accomplished by using two work rolls. Because the rolls rotate with a surface velocity exceeding the speed of the incoming metal, friction along the contact interface grabs the metal and propels it forward. The amount of deformation that can be achieved in a single pass between a given pair of rolls depends on the frictional conditions along the interface. If too much deformation is attempted, the rolls will simply skid over stationery metal, while too little deformation per pass results in excessive cost.

The main advantage of rolling lies in its ability to produce desired shapes from relatively large pieces of metals at very high speeds in a somewhat continuous manner. Many engineering metals are often cast into ingots and then processed by hot rolling into blooms, slabs, and billets (Fig. 16.5), which are then rolled into other products, such as plate, sheet, tube, rod, bar, and structural shapes. Rolling of blooms, slabs, billets, plates, and structural shapes is usually done at temperatures above the recrystallization temperature, where large reductions in height or thickness are possible with moderate forming pressures. Sheet and strip are often cold rolled in order to maintain closer thickness tolerances and provide superior surface finishes.

The three principal types of rolling mills are the two-high, three-high, and four-high mills shown in Fig. 16.6. As their names imply, this classification is based on the way the rolls are arranged in the housings. Two-high mills may be either pull-over mills or reversing mills. In pull-over mills, the rolls run in only one direction. The workpiece must be returned over the top of the mill for further rolling. Reversing mills employ rolls in which the direction of rotation can be reversed. Rolling then takes place alternately in two opposite directions. Reversing mills are among the most widely used in industry and can be used to produce slabs, blooms, plates, billets, rounds, and partially formed sections suitable for rolling into finished shapes on other mills. In three-high mills, the top and bottom rolls rotate in the same direction, while the middle roll rotates in the opposite direction. This allows the workpiece to be passed back and forth alternately through the top and middle rolls, and then through the bottom and middle rolls without reversing the direction of roll rotation. Since the roll-work contact length is reduced with a smaller roll radius, leading to lower forces, torque, and power, the four-high rolling mill uses two smaller-diameter rolls to contact the work, with two larger backing rolls for support. The larger backup rolls reinforce the smaller work rolls, thus allowing fairly large reductions without excessive amounts of roll deflection. Four-high mills are used to produce wide plates and hot-rolled or cold-rolled sheet, as well as strip of uniform thickness.

Another important type of mill that uses smaller working rolls against the workpiece is the cluster mill, the most common being the Sendzimir mill. In a typical Sendzimir mill design (Fig. 16.7), each work roll is supported through its entire length by two rolls, which in

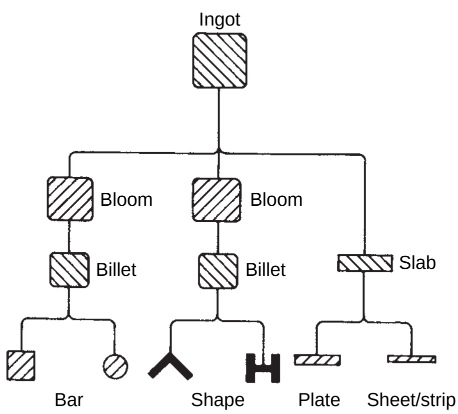

Fig. 16.5 A bloom has a nearly square cross section with an area larger than 32 in.^{2} (206 cm^2); the minimum cross section of a billet is about 1.5 × 1.5 in. (3.8 × 3.8 cm), and a slab is a hot-rolled ingot with a cross-sectional area greater than 16 in.^{2} (103 cm^2) and a section width of at least twice the section thickness. Plates are generally thicker than 0.25 in. (0.64 cm), whereas sheets are thinner-gage materials with very large width-to-thickness ratios. Sheet material with a thickness of a few thousandths of an inch is referred to as foil.

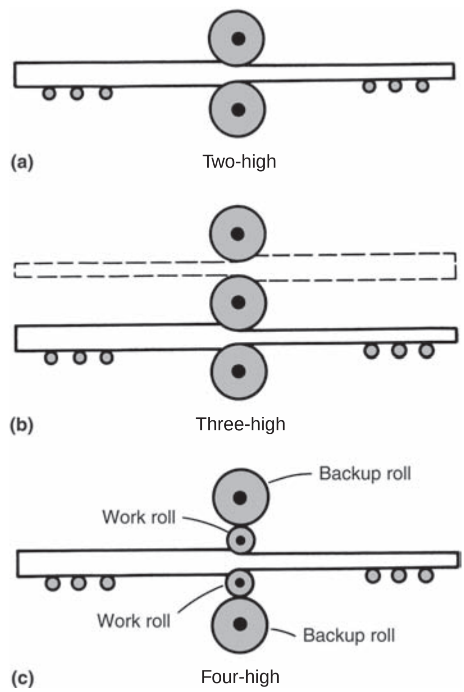

Fig. 16.6 Common types of rolling mills. Source: Ref 5

turn are supported by three rolls. These rolls transfer roll separating forces through four large backup rolls to a rigid cast steel housing. Sendzimir mills are used for the cold rolling of sheet and foil to precise thicknesses. To achieve higher throughput rates in standard products, a tandem rolling mill is often used, consisting of a series of rolling stands. However, with each rolling step, work velocity increases so the rolling speeds at each stand must be synchronized. Hot rolling is also used to produce structural shapes. As shown in the example for an I-beam in Fig. 16.8, multiple stands are used to gradually produce the desired shape.

After hot rolling, many products undergo further processing by cold rolling. Prior to cold rolling, coils of steel are usually annealed to remove any cold work introduced during hot rolling. Cold rolling, usually performed at room temperature, permits the thickness of the strip to be closely controlled while also improving the surface quality. Since cold rolling work hardens the metal, sheet metal that is going to be subsequently used for forming or pressing operations is annealed to soften it. Depending on the particular equipment and cold rolling parameters, different patterns of residual stresses can be produced in cold-rolled sheet (Fig. 16.9). If the product is going to be used in the cold-rolled state, it is better to use smaller rollers and/or smaller reductions per pass to produce compressive residual stresses on the surface.

Another form of cold processing is cold drawing (Fig. 16.1). Metal in rod form is drawn through a series of dies that progressively reduce the rod circumference to produce wire. The drawing process substantially increases the material tensile strength. Drawn wires can be spun into huge cables that have very high strengths.

16.4 Forging

During forging, large compressive forces are used to deform the metal into a new shape. There are two main reasons for forging: (1) forging improves the properties and homogeneity of the microstructure; therefore, forging is often used to prepare cast ingots for other bulk deformation processes, such as hot rolling; and (2) forging is also a major method of producing semifinished or near-net shapes. Forging processes can be described as open-die forging or closed-die forging (Fig. 16.10). Open-die forging is carried out between two flat dies or dies with very simple configurations, such as V-shaped or semicircular cavities. In closed-die forging, the metal to be forged is placed between two dies that have the upper and lower impressions of the desired shape of the forging. Closed-die forging can be carried out by using a single pair of dies or with multiple impression dies. Hammers or presses are used to apply the forces to the

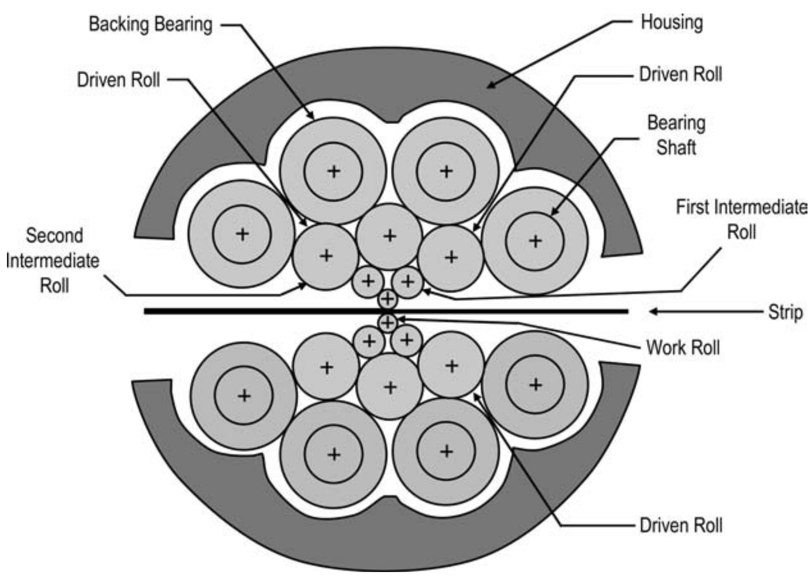

Fig. 16.7 Sendzimir mill. Source: Ref 5

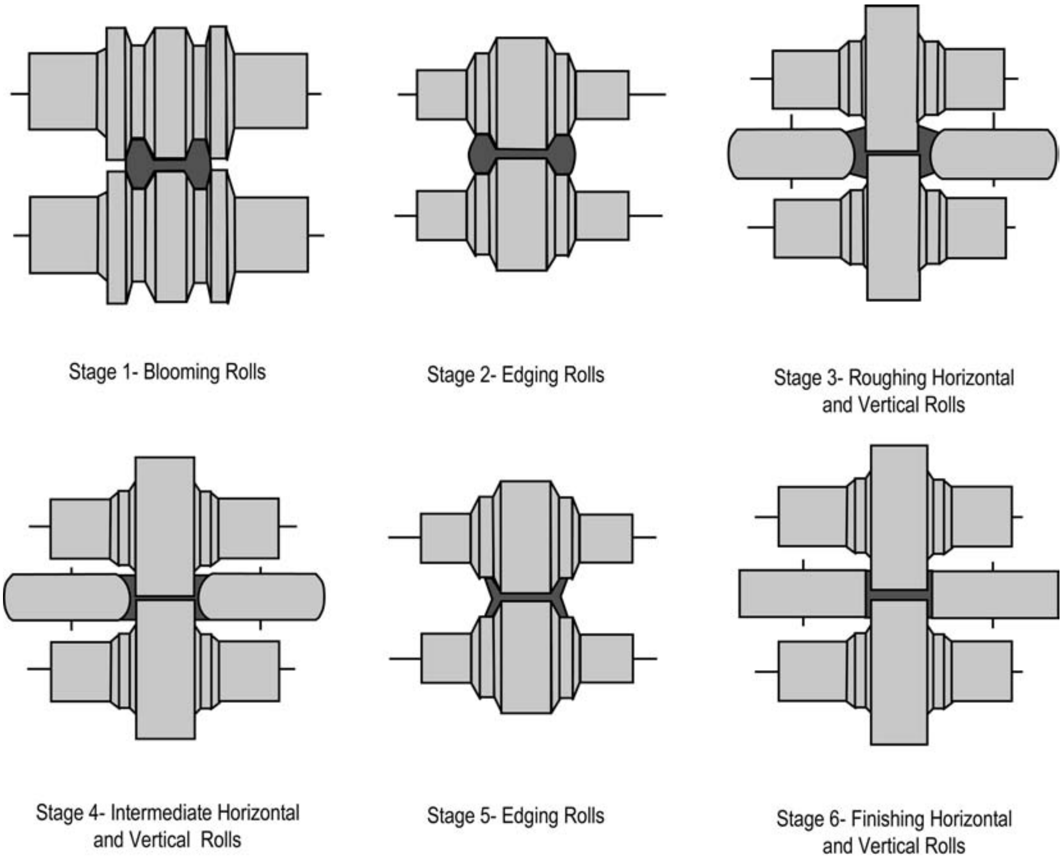

Fig. 16.8 Rolling of an I-beam. Source: Ref 6

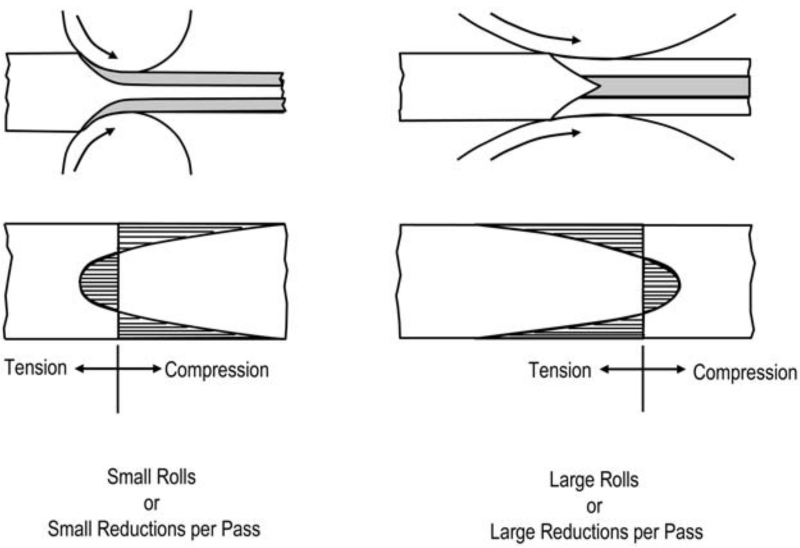

Fig. 16.9 Residual stress patterns produced by rolling. Source: Ref 6

workpiece, which is usually heated to above its recrystallization temperature, although cold forging is also used to produce finished shapes.

During the breakdown of cast ingots and working by forging, nonuniformities in alloy chemistry, second-phase particles, inclusions, and the crystalline grains are broken up and redistributed, improving the homogeneity of the microstructure. This is important in cast structures that are going to be processed by hot rolling. Without the refinement of the microstructure due to forging, the ingot will often crack under the forces of the rolling operation. When the deformation produced by forging becomes large, such as during the forging of a structural shape, the microstructure becomes aligned in the direction of greatest metal flow. This directional pattern of grains and second-phase particles is known as the grain flow pattern. This pattern is responsible for the familiar fiber structure of forgings (Fig. 16.11). It also produces a directional variation in strength, ductility, fracture toughness, and fatigue strength. This anisotropy in properties is greatest between the working (longitudinal) direction and the transverse direction. In a properly designed forging, the largest stress should be parallel to the fibrous structure, and the parting line of the dies should be located so as to minimize disruption to the grain flow lines.

Metals can be forged using hammers, mechanical presses, or hydraulic presses. Hammer forging operations can be conducted with either gravity or power drop hammers and are used for both open- and closed-die forgings. Hammers deform the metal with high deformation speed; therefore, it is necessary to control the length of the stroke, the speed of the blows, and the force being exerted. Hammer operations are frequently used to conduct preliminary shaping prior to closed-die forging. Both mechanical and screw presses are used for forging moderate-sized parts of modest shapes and are often used for high-volume production runs. Mechanical and screw presses combine impact with a squeezing action that is more compatible with the flow characteristics of some metals than are hammer processes. Hydraulic presses are the best method for producing large and thick forgings, because the deformation rate is slower and more controlled than with hammers or mechanical/screw presses. The deformation or strain rate can be very fast ($>10\ s^{-1}$) for processes such as hammer forging or very slow ($<0.1\ s^{-1}$) for hydraulic presses. Since higher strain rates increase the flow stress (decrease forgeability), hydraulic presses are usually preferred for forging alloys with low forgeability. Hydraulic presses are available in the range of 225 to 34,000 kg (500 to 75,000 lb) and can produce forgings up to approximately 1360 kg (3000 lb). A large hammer forge and hydraulic press are shown in Fig. 16.12.

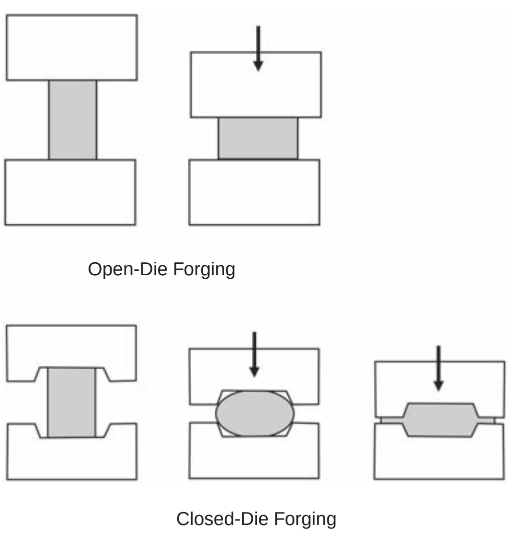

Fig. 16.10 Open- and closed-die forging

Open-die forgings, also know as hand forgings, are produced in dies that do not provide lateral restraint during the forging operation. In this process, the metal is forged between either flat or simply-shaped dies. This process is used to produce small quantities where the small quantities do not justify the expense of matched dies. Although open-die forgings somewhat improve the grain flow of the material, they offer minimal economic benefit in reduced machining costs. Open-die forging is often used to produce preforms for closed-die forging.

Flow localization, caused by the formation of a dead-metal zone between the workpiece and the tooling, is a common problem with large reductions. This can arise from poor lubrication at the workpiece/tool interface. Upsetting is the working of a metal such that the cross-sectional area of all or part of the workpiece is increased. Upsetting of a cylinder with poorly lubricated platens is shown in Fig. 16.13. When the workpiece is constrained from sliding at the interface, it takes on a barrellike shape, and a friction-hill pressure distribution is created over the interface. The inhomogeneity of deformation throughout the cross section leads to a dead-metal zone at the tool interface and a region of intense shear deformation. If the shear deformations become too high, the forging can fracture.

Closed-die forging shapes the part between two die halves; thus, productivity is increased, albeit at the expense of higher die costs. Excess metal is allowed to escape in the flash; therefore, pressure is kept within safe limits, while die filling is ensured. More complex shapes, thinner walls, and thinner webs may necessitate forging in a sequence of die cavities. At high width-to-thickness ratios, friction sets a limit to minimum web thickness that decreases with effective lubrication. During true closed-die forging, the material is trapped in the die cavity. An important consideration when closed-die forging is for the metal to flow during forging to fill the cavities of the impression die. The forgeability of the metal is a way of expressing this capability. Poor forgeability can be caused by rupture before the die is filled or by a high flow strength, which causes the metal to flow past recesses without filling them, or causes underfilling with the maximum loads available.

Closed-die forgings are produced by forging ingots, plates, or extrusions between a matched set of dies. Closed-die forging uses progressive sets of dies to gradually shape the part to near-net dimensions. Die forgings can be subdivided into four categories from the lowest cost, least intricate to the highest cost, most intricate. A comparison of the relative amount of part definition for these different forging processes is shown in Fig. 16.14.

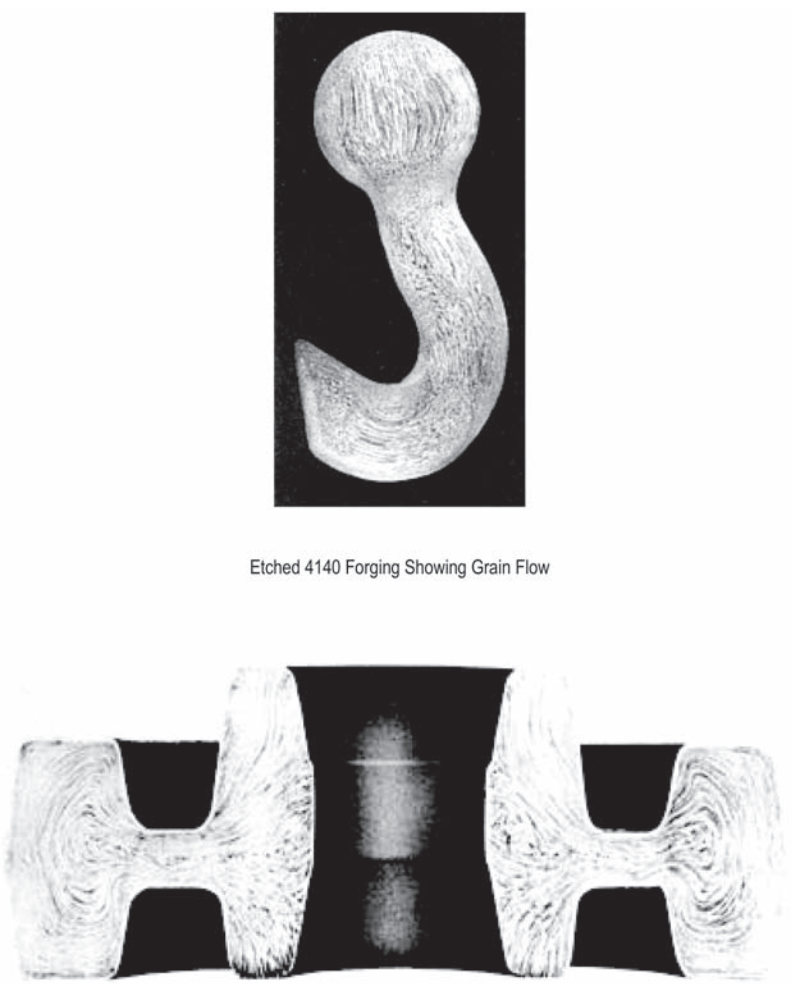

Fig. 16.11 Grain flow from forging. Source: Ref 7

Blocker forgings may be chosen if the total quantities are small (e.g., 200). Since they have large fillet and corner radii, extensive machining is required to produce a finished part. The fillets are approximately 2 times the radius, and the corner radii approximately 1.5 times the radii of conventional forgings. Therefore, a blocker forging costs less than a conventional forging but requires more machining. Finish-only forgings are similar to blocker forgings in that only one set of dies is used; however, since they have one more squeeze applied, they have somewhat better part definition. Fillets are approximately 1.5 times the radius of conventional forgings, with corner radii about the same as conventional forgings. A quantity of approximately 500 may justify the use of finish-only forgings.

Conventional forgings require two to four sets of dies, with the first set producing a blocker-type forging that is subsequently finished in the other sets. This is the most common type of forging and is usually specified for quantities of 500 or more. Conventional forgings have more definition and require less machining than blocker forgings, but the die cost is higher.

High-definition forgings contain even better definition and tolerance control than conventional forgings, with less machining costs. These forgings are near-net shape forgings produced on multiple die sets. For some applications, some of the forged surfaces may not require machining.

Precision forgings produce the best component definition and highest quality but are, of course, the most expensive. These forgings have tighter tolerances than those produced by even high-definition forgings, with better grain flow. Minimal or no machining is required to finish these forgings.

Other common forging methods include roll forging, orbital or rotary forging, spin forging, ring rolling, and mandrel forging. The choice of a particular forging method depends on the shape required and the economics of the number of pieces required traded off against higher quality and lower machining costs.

Isothermal forging, shown in comparison with conventional forging in Fig. 16.15, is a process where the dies are maintained at the same temperature as the workpiece. Since this temperature is often on the order of 980 to

Large Forge Hammer

(a)

15,000 Ton Hydraulic Press

(b) *Ladish*

Fig. 16.12 Forging equipment

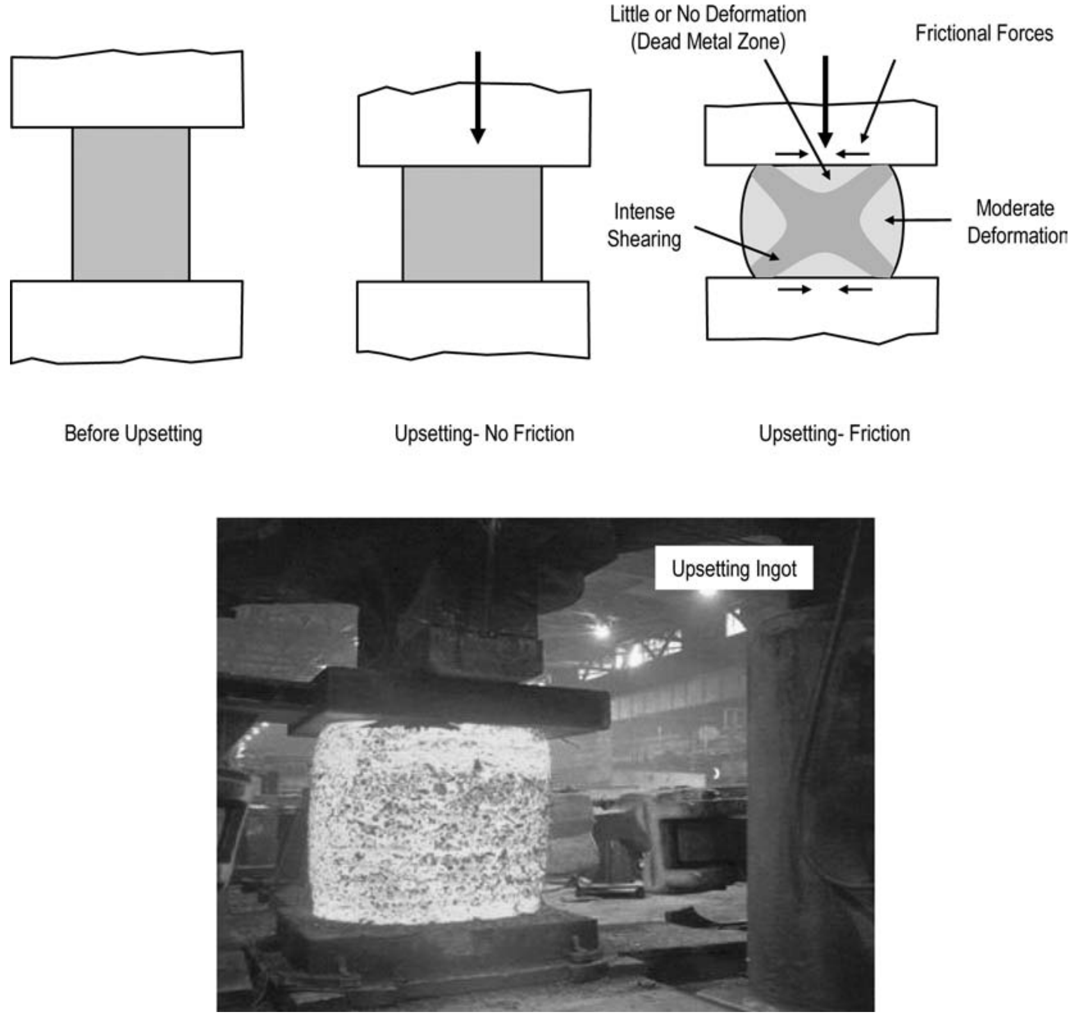

Fig. 16.13 Upsetting

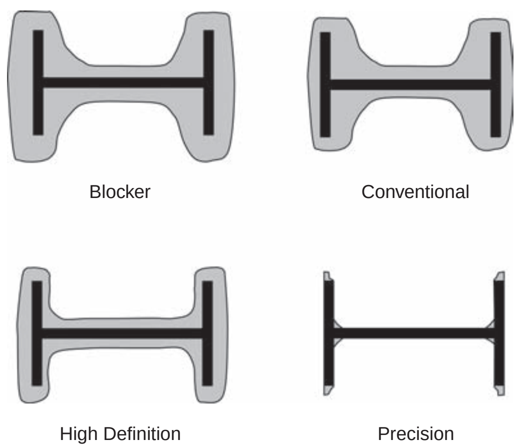

Fig. 16.14 Part definition produced by different die forging methods. Source: Ref 8

1095 °C (1800 to 2000 °F), the dies are usually made of titanium-zirconium-molybdenum for elevated-temperature strength. In addition, isothermal forging is conducted in a vacuum or inert atmosphere in order to protect the part and die material from oxidation. Compared to conventional forging, isothermal forging deformation rates are slow; hydraulic press speeds of approximately 0.3 cm/min (0.1 in./min) are typical. The slow strain rate helps to control both the shape of the forged part and the microstructure. Accurate temperature and strain rate can be controlled by sensors in conjunction with the press equipment to give a closed-loop control system. The slower production rate is largely offset by the ability to forge complex shapes to closer tolerances, which leads to less machining

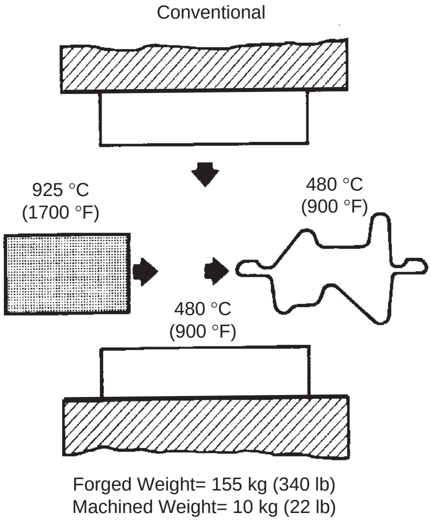

Fig. 16.15 Comparison of conventional and isothermal forging. Source: Ref 8

and substantial material savings. In addition, a large amount of deformation is accomplished in one operation. Pressures are low, and uniform microstructures are achieved. For example, a finish-machined 68 kg (150 lb) Astroloy nickel-base superalloy disk started with an as-forged weight of 111 kg (245 lb) for conventional forging versus 73 kg (160 lb) for a corresponding isothermal forging.

Cold forging, when conducted so that a complex shape is formed in a single step, requires special lubricants, often with a conversion coating. Alternatively, the shape can be developed by moving the bar or slug through a sequence of cavities using a liquid lubricant. Cold forging is often combined with cold extrusion. It is the preferred process for mass producing near-net shape parts such as bolts, nuts, rivets, and many automotive and appliance components.

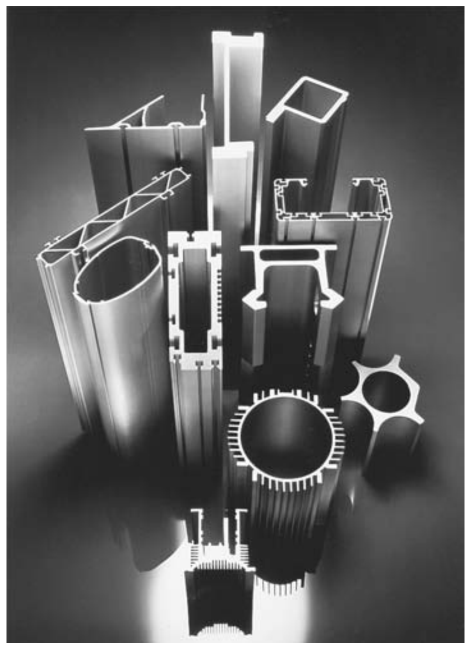

Fig. 16.16 Aluminum extrusions. Source: Ref 9

16.5 Extrusion

Extrusion is a bulk deformation process in which a metal under high pressure is reduced in cross section by forcing it through a die. During extrusion, the metal billet is forced by a hydraulic ram through a die so that the metal is continuously deformed into a long length of metal with the desired cross section. Most metals are hot extruded, since their resistance to deformation is lower than in the cold state. The extrusion process is used primarily for producing bar shapes, tubes, and irregular shapes, such as those shown in Fig. 16.16.

In hot extrusion, a heated billet is forced through the die opening. The temperature used for hot extrusion depends on the alloy and can range from as low as 95 °C (200 °F) for lead to

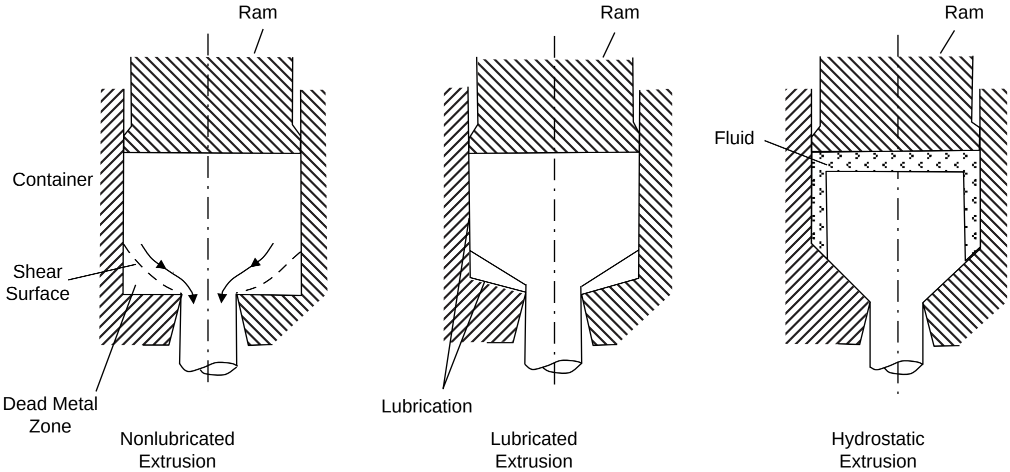

Fig. 16.17 Extrusion processes. Source: Ref 10

1260 °C (2300 °F) for steel and nickel alloys. Hot extrusion is used to produce long, straight metal products of constant cross section, such as bars, solid and hollow sections, tubes, wires, and strips from materials that cannot be formed by cold extrusion. The three basic types of hot extrusion are nonlubricated, lubricated, and hydrostatic (Fig. 16.17). In nonlubricated hot extrusion, the material flows by internal shear, and a dead-metal zone is formed in front of the extrusion die. Lubricated extrusion, as the name implies, uses a suitable lubricant, usually glass powder or grease, between the extruded billet and the die. With hydrostatic extrusion, a fluid film present between the billet and the die exerts pressure on the deforming billet. Hydrostatic extrusion is used primarily when conventional lubrication is inadequate, for example, in the extrusion of special alloys or clad materials. For all practical purposes, hydrostatic extrusion can be considered an extension of the lubricated hot extrusion process.

Nonlubricated hot extrusion uses no lubrication on the billet, container, or die. It can produce very complex sections with mirror-surface finishes and close dimensional tolerances that are considered to be net extrusions. There are basically two methods of hot extruding materials without lubrication: (1) forward, or direct, extrusion; and (2) backward, or indirect, extrusion (Fig. 16.18). In direct extrusion, the metal billet is placed in the container of an extrusion press and forced directly through the die by the hydraulic ram. During the indirect extrusion process, a hollow ram holds the die, which is forced onto the metal billet. The billet is held in the extrusion container during this process. The advantage of indirect extrusion is that there is approximately a 25 to 30% reduction in maximum load relative to direct extrusion, and since no friction is produced between the billet and container, the temperatures are lower, leading to longer die lives. The disadvantage of indirect extrusion is that impurities or defects on the

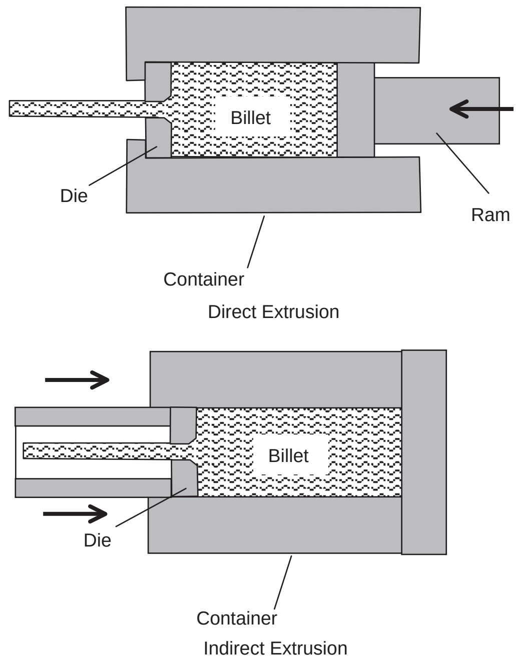

Fig. 16.18 Direct and indirect extrusion

billet surface affect the surface finish of the extrusion and are not automatically retained as a shell or discard in the container. As a result, machined billets are used in many cases. In addition, the cross-sectional area of the extrusion is limited by the size of the hollow stem.

Generally, aluminum alloys are extruded without lubrication, but copper alloys, titanium alloys, alloy steels, stainless steels, and tool steels are extruded with a variety of graphite and glass-based lubricants. The choice between grease and glass lubricants is based mainly on the extrusion temperature. At low temperatures, since lubrication is used only to reduce friction, greases and graphite are commonly used. At temperatures above 980 °C (1800 °F), glasses are used because, in addition to providing lubrication, they help to thermally insulate the tooling from overheating. The lubricating film can also impede oxidation.

In hydrostatic extrusion, the billet in the container is extruded through the die by the action of a liquid pressure medium rather than by direct application of the load with a ram. The process of pure hydrostatic extrusion differs from conventional extrusion processes in that the billet is completely surrounded by a fluid, which is sealed off and pressurized sufficiently to extrude the billet through the die. Hydrostatic extrusion can be done hot, warm, or cold and can be used to extrude brittle materials that cannot be processed by conventional extrusion. Hydrostatic extrusion also allows greater reductions in area than either cold or conventional hot extrusion.

In cold extrusion, the slug or preform enters the extrusion die at room temperature. Any subsequent increase in temperature, which may amount to several hundred degrees, is caused by the conversion of the work of deformation into heat. Cold extrusion can be conducted by direct, indirect, or combined direct-indirect processes. Aluminum and aluminum alloys, copper and copper alloys, low- and medium-carbon steels, modified carbon steels, low-alloy steels, and stainless steels are the metals that are most commonly cold extruded. Cold extrusion competes with alternative metal forming processes such as cold heading, hot forging, hot extrusion, machining, and sometimes casting. Cold extrusion is used when the process is economically attractive because of savings in material; reduction or elimination of machining and grinding operations, because of the good surface finish and dimensional accuracy of cold-extruded parts; and elimination of heat treating operations because of the increase in the mechanical properties of cold-extruded parts. Impact extrusion is a term employed for the cold extrusion of thin-walled products such as toothpaste tubes.

16.6 Sheet Metal Forming Processes

Sheet metal forming processes usually employ hot- or cold-rolled sheet or strip material that is normally cold formed into the desired shape. Deformation is primarily by tension or combined tension-compression, and the limits are set by the formability of the material and only rarely by force or die pressure. Many sheet metal parts are fairly simple in shape, as shown in Fig. 16.19.

16.7 Blanking and Piercing

Blanking is a process in which a shape is sheared from a larger piece of sheet, while piercing produces a hole in the sheet by punching out a slug of metal (Fig. 16.20). Both blanking and piercing operations are usually performed in a punch press. The clearance between the punch and die must be controlled to obtain a uniform shearing action. Clearance is the distance between the mating surfaces of the punch and die, usually expressed as a percentage of sheet thickness. The walls of the die opening are tapered to minimize sticking, and the use of lubricants, such as mineral oil mixed with small quantities of fatty oils, also reduces sticking tendencies. Dull cutting edges on punches and dies have effects similar to excessive clearance, with burrs becoming excessive. With sharp tools and proper clearance, the cuts are clean without evidence of secondary shearing or excessive burring. When the clearance is too small, secondary shearing can occur, and if the clearance is too large, the sheared edge will have a large radius and a stringy burr.

16.8 Bending

In bending (Fig. 16.21), the sheet is placed over a die and pressed down by a punch that is actuated by the hydraulic ram of a press brake. The material is stressed beyond the yield strength but below the ultimate tensile strength. The surface area of the material does not change much. Bending usually refers to deformation about one axis and is a flexible process by which many different shapes can be produced. Standard die sets are used to produce a wide variety of shapes. The material is placed on the die, positioned in the machine with stops and/or gages, and is held in place with holddowns. The upper part of the press, the ram with the appropriately shaped punch, descends and forms the bend. Press brakes normally have a capacity of

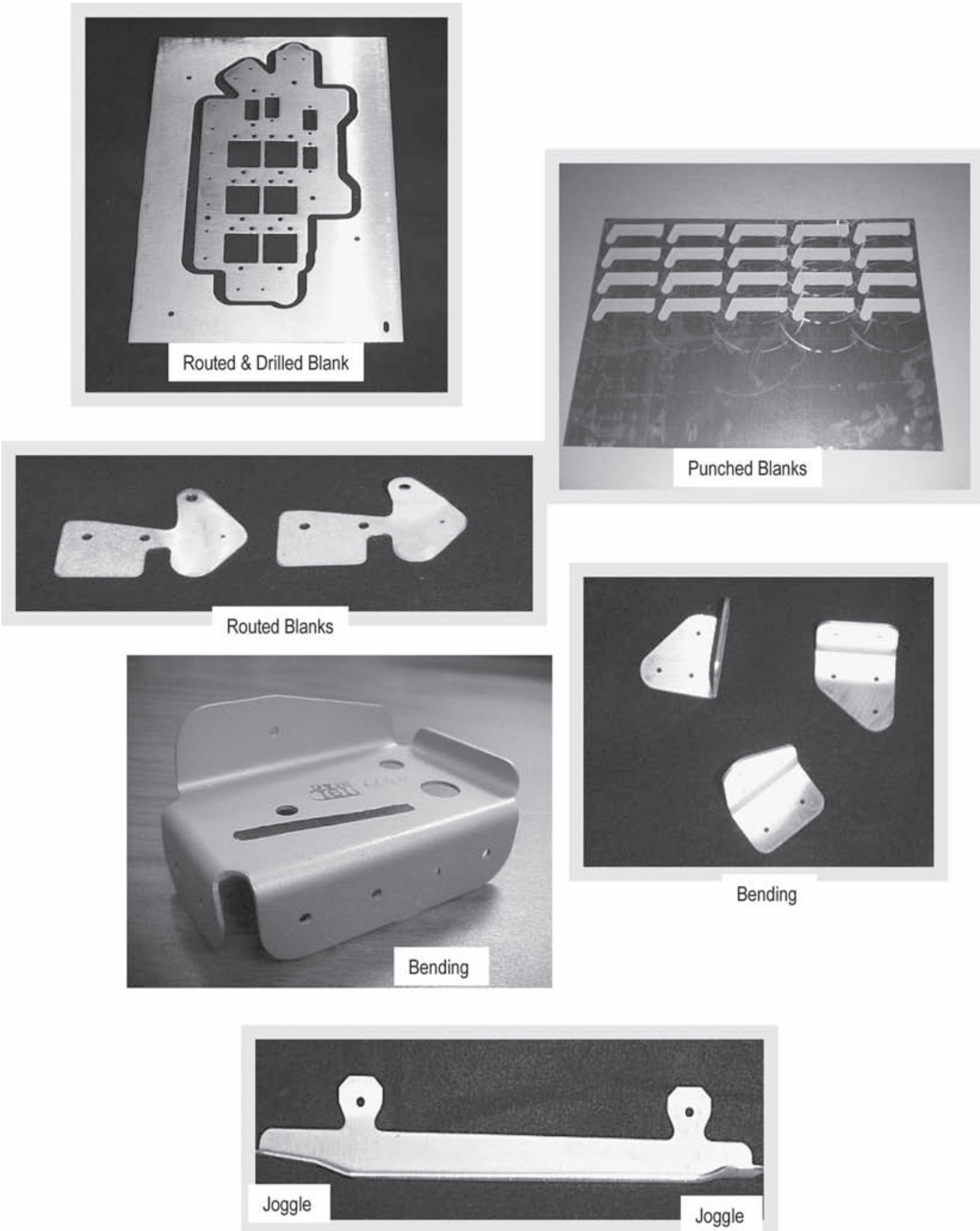

Fig. 16.19 Simple sheet metal parts

18 to 181 Mg (20 to 200 tons) to accommodate stock from 1 to 5 m (3 to 15 ft). Larger and smaller presses are used for specialized applications.

Springback is the partial return of the part to its original shape after forming. The amount of springback is a function of the yield strength of the material being formed, the bend radius, and the sheet thickness. Springback is compensated by overbending the material beyond the final angle so that it springbacks to the desired angle. The springback allowance (i.e., the amount of overbend) increases with increasing yield strength and bend radius but varies inversely with sheet thickness. The smallest angle that can be safely bent, called the minimum bend radius, depends on the yield strength and on the design, dimensions, and conditions of the tooling. The most severe bends can be made across the rolling direction. If similar bends are to be made in two or more directions, it is best to make all bends at an angle to the direction of rolling.

Bending a sheet along a curved line is termed flanging. Circular or other close-shaped flanges (collars) are mass produced in preparation for joining tubes and fasteners to sheet, as in heat exchangers. Limits are set by fracture in a stretch flange and by buckling in a shrink flange. Related processes are flanging and necking of tubes and cans, as for beverage cans.

16.9 Stretch Forming

In stretch forming (Fig. 16.22), the material is stretched over a tool to produce the desired shape. The blank is firmly clamped at much or all of its circumference, and the shape is developed by penetration of a punch, at the expense of thickness. Small quantities can be produced with only a punch, although at higher material cost, as in the aircraft industry. Mating dies with carefully designed blankholders are more economical for the large quantities typical of the

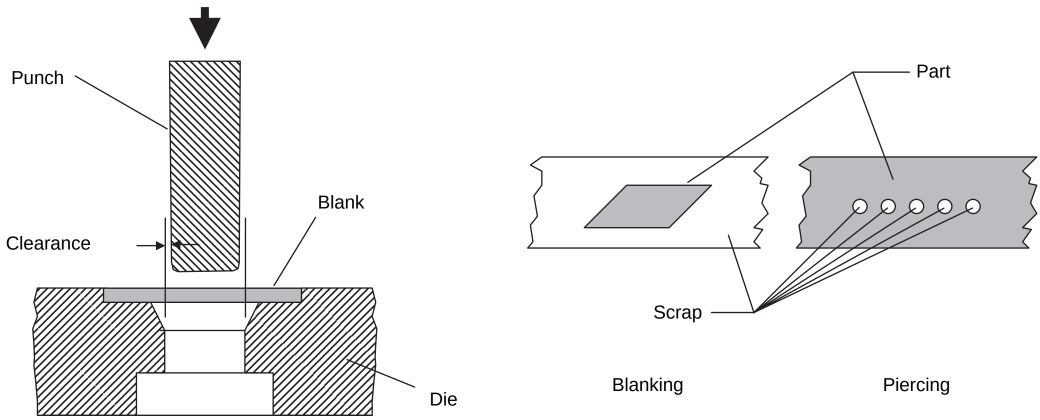

Fig. 16.20 Blanking and piercing. Source: Ref 8

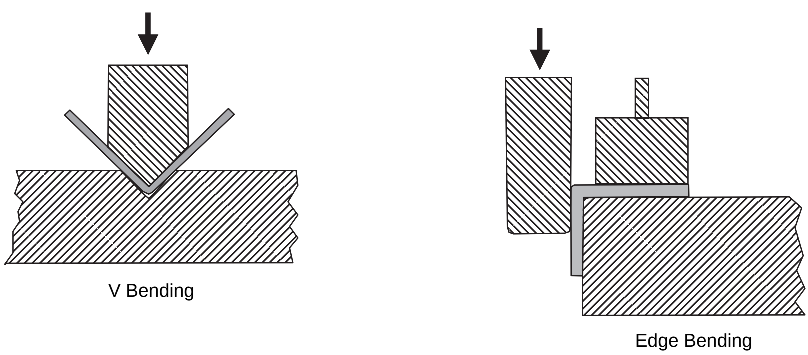

Fig. 16.21 Bending. Source: Ref 8

automotive and appliance industries. An important aspect is control of or compensation for elastic recovery (springback), which distorts the shape. Large compound shapes can be formed by stretching the sheet both longitudinally and transversely. In addition, extrusions are frequently stretch formed to final curvature. Variants of stretch forming include stretch draw forming, stretch wrapping, and radial draw forming. Forming lubricants are recommended except when self-lubricating, smooth-faced plastic dies are used; however, the use of too much lubricant can result in workpiece bucking. Material properties that help in stretch forming are a high elongation, a large spread between the yield and ultimate strengths (called the forming range), toughness, and a fine grain structure. Alloys with a narrow spread between the yield and ultimate strengths are more susceptible to local necking and failure. For example, when the aluminum alloy 7075 has been quenched but not aged (W condition), it has a yield strength of 140 MPa (20 ksi), an ultimate strength of 330 MPa (48 ksi), a forming range of 190 MPa (28 ksi) (330 − 140 MPa), and a stretchability rating of 100. In contrast, 7075 that has been aged to peak strength (T6) has a yield strength of 460 MPa (67 ksi), an ultimate strength of 525 MPa (76 ksi), a forming range of only 65 MPa (9 ksi), and a stretchability rating of only 10.

16.10 Drawing

In drawing, a blank of sheet metal is restrained at the edges, and the middle section is forced by a punch into a die to stretch the metal into a cup-shaped drawn part, as shown for deep drawing in Fig. 16.23. Drawn components can be just about any cross section but are usually circular or rectangular. Drawing can be either shallow or deep, depending on the amount of deformation. For shallow drawing, the depth of draw is less than the smallest dimension of the opening; otherwise, it is deep drawing. Drawing leads to wrinkling and puckering at the edge where the sheet metal is clamped. Ears (Fig. 16.24) are usually removed by a separate trimming operation.

In drawing, the shape is developed by drawing material into the die, and the average thickness is approximately preserved. The flange is in circumferential compression and forms wrinkles, unless the blank is thick relative to the blank diameter or is adequately restrained with a blankholder. Fracture occurs at the base or in the wall if stresses exceed the strength of the partly formed cup; therefore, a limit is set to the attainable reduction in diameter or, as more frequently expressed, a limiting draw ratio

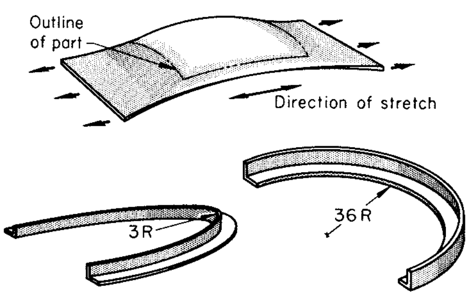

Fig. 16.22 Stretch forming. Source: Ref 11

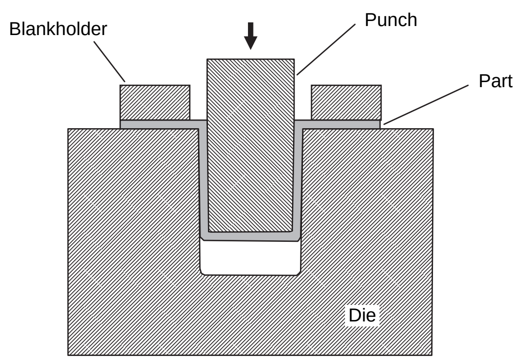

Fig. 16.23 Deep drawing. Source: Ref 8

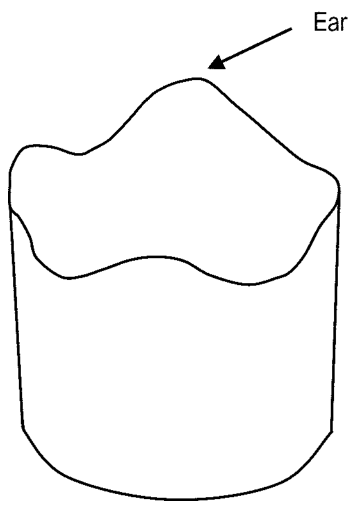

Fig. 16.24 Earing in deep-drawn cup

(LDR = diameter of blank/diameter of cup) is reached. The LDR is a system property, affected by material, especially the *r*-value, die design, and lubricant. (An explanation of the significance of the *r*-value can be found in section 19.9.1. in Chapter 19, "Plain Carbon Steels," in this book.) Cups deeper than allowed by the LDR are produced by redrawing, or reverse redrawing, or by thinning the wall by ironing (increasing length by reducing wall thickness while maintaining a constant inner diameter).

Punch presses are used for most deep-drawing operations. In a typical deep-drawing operation, a punch or male die pushes the sheet into the die cavity while it is supported around the periphery by a blankholder. Single-action presses can be operated at 27 to 43 m/min (90 to 140 ft/min), while double-action presses operate at 12 to 30 m/min (40 to 100 ft/min) for mild draws and at less than 15 m/min (50 ft/min) for deep draws. Clearances between the punch and die are important. Excessive clearance can result in wrinkling of the sidewalls of the drawn shell, while insufficient clearance increases the force required for drawing and tends to burnish the part surfaces. If the punch radius is too large, wrinkling can result, and if the radius is too small, sheet fracture is a possibility. Draw punches and dies should have a surface finish of 0.4 μm (16 μin.) or less for most applications. Tools are often chrome plated to minimize friction and dirt that can damage the part finish. Lubricants for deep drawing must allow the blank to slip readily and uniformly between the blankholder and die. Stretching and galling during drawing must be avoided. During blank preparation, excessive stock at the corners must be avoided because it obstructs the uniform flow of metal under the blankholder, leading to wrinkles or cracks. Severe forming operations of relatively thick or large blanks of high-strength alloys generally must be conducted at elevated temperature, where the lower strength and partial recrystallization aids in forming, but the time at temperature should be minimized to limit grain growth.

16.11 Rubber Pad Forming

Rubber pad forming uses a rubber pad to exert nearly equal pressure over the part as it is formed down over a form block. Rubber pad forming, and a closely related process, fluid cell forming, are shown in Fig. 16.25. The rubber pad acts somewhat like a hydraulic fluid, spreading the force over the surface of the part. The pad can either consist of a solid piece or may be several pieces laminated together. The pad is usually in the range of 15 to 30 cm (6 to 12 in.) thick and must be held in a sturdy retainer, because the pressures generated can be as high as 140 MPa (20 ksi). Rubber pad forming can often be used to form tighter radii and more severe contours than other forming methods because of the multidirectional nature of the force exerted on the workpiece. The rubber acts somewhat like a blankholder, helping to eliminate the tendency for wrinkling. This process is very good for making sheet metal parts with integral stiffening beads. Most rubber pad forming is conducted on sheet 1.6 mm (0.063 in.) or less in thickness; however, material as thick as 16 mm (0.625 in.) has been successfully formed. Fluid cell forming, which uses a fluid cell to apply pressure through an elastomeric membrane, can form even more severe contours than rubber pad forming. Due to the high pressures employed in this process, as high as 100 to 140 MPa (15 to 20 ksi), many parts can be formed in one operation with minimal or no springback. However, fluid cell forming presses are usually expensive.

16.12 Superplastic Forming

Superplasticity is a property that allows sheet to elongate to quite large strains without localized necking and rupture. In uniaxial tensile testing, elongations to failure in excess of 200% are usually indicative of superplasticity. Micrograin superplasticity occurs in some materials with a fine grain size, usually less than 10 μm, when they are deformed in the strain range of 0.00005 to 0.01/s at temperatures greater than 0.5 T_m, where T_m is the absolute melting point. Although superplastic behavior can produce strains in excess of 1000% (Fig. 16.26), superplastic forming (SPF) processes are generally limited to approximately 100 to 300%. The advantages of SPF include the ability to make part shapes not possible with conventional forming, reduced forming stresses, improved formability with essentially no springback, and reduced machining costs. The disadvantages are that the process is rather slow, and the equipment and tooling can be relatively expensive.

The main requirement for superplasticity is a high strain-rate sensitivity. In other words, the strain-rate sensitivity, *m*, should be high where *m* is defined as:

$$m = \frac{d(\ln \sigma)}{d(\ln \dot{\varepsilon})} \quad \text{(Eq 16.3)}$$

where *m* is the strain-rate sensitivity, σ is the flow stress, and $\dot{\varepsilon}$ is the strain rate.

The strain-rate sensitivity describes the ability of a material to resist plastic instability or necking. For superplasticity, *m* is usually greater than 0.5, with the majority of superplastic materials having an *m* value in the range of 0.4 to 0.8, where a value of 1.0 would indicate a perfectly superplastic material. The presence of a neck in a material undergoing a tensile strain results in a locally high strain rate and, for a high value of *m*, to a sharp increase in the yield stress within the necked region; that is, the neck undergoes strain hardening, which restricts its further development. Therefore, a high strain-rate sensitivity resists neck formation and leads to the high tensile elongations observed in superplastic materials. The yield stress decreases and the strain-rate sensitivity increases with increasing temperature and decreasing grain size. The elongation to failure tends to increase with increasing *m*.

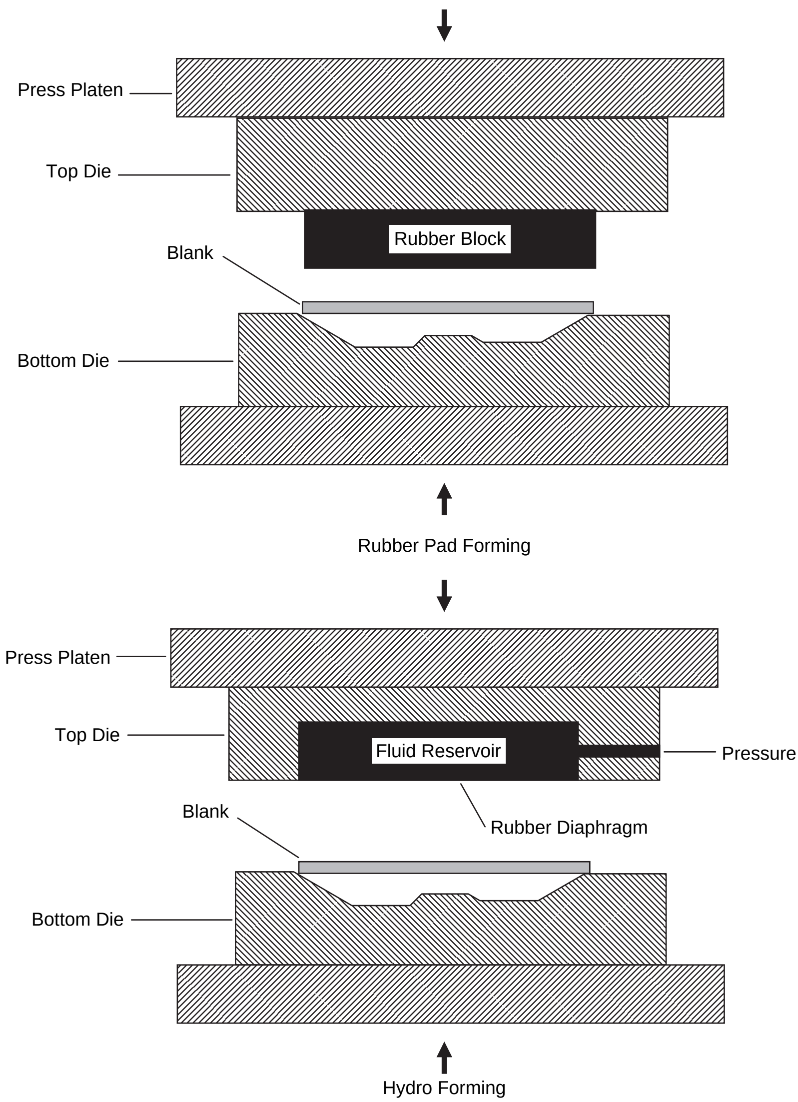

Fig. 16.25 Rubber pad and hydro forming. Source: Ref 8

Superplasticity depends on microstructure and exists only over certain temperature and strain-rate ranges. A fine grain structure is a prerequisite since superplasticity results from grain rotation and grain-boundary sliding, and increasing grain size results in increases in yield stress. Equiaxed grains are desirable because they contribute to grain-boundary sliding and grain rotation. A duplex structure also contributes to superplasticity by inhibiting grain growth at elevated temperature. Grain growth inhibits superplasticity by increasing the flow stress and decreasing *m*. The Ashby and Verrall model for superplasticity, based on grain-boundary sliding with diffusional accommodation, is shown in Fig. 16.27, in which grains switch places with their neighbors to facilitate elongation. Since the grains are not all the same size, some rotation must also take place. Slow strain rates are necessary to allow the

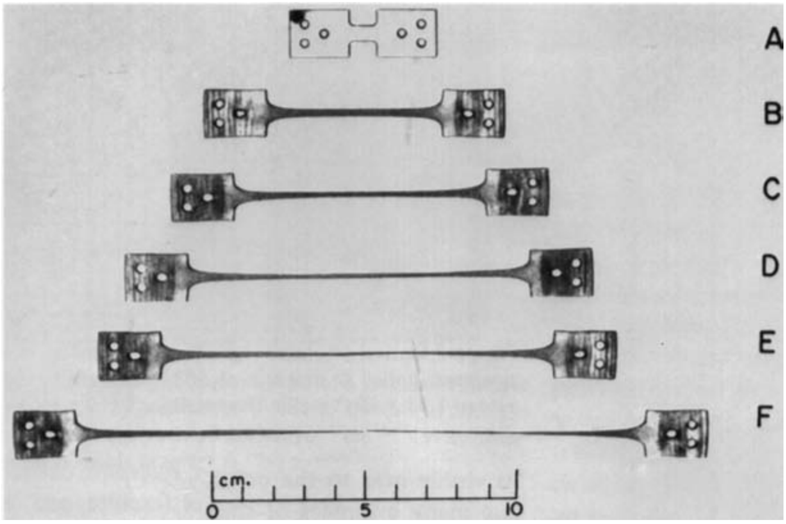

Fig. 16.26 Superplastic elongation. Source: Ref 12

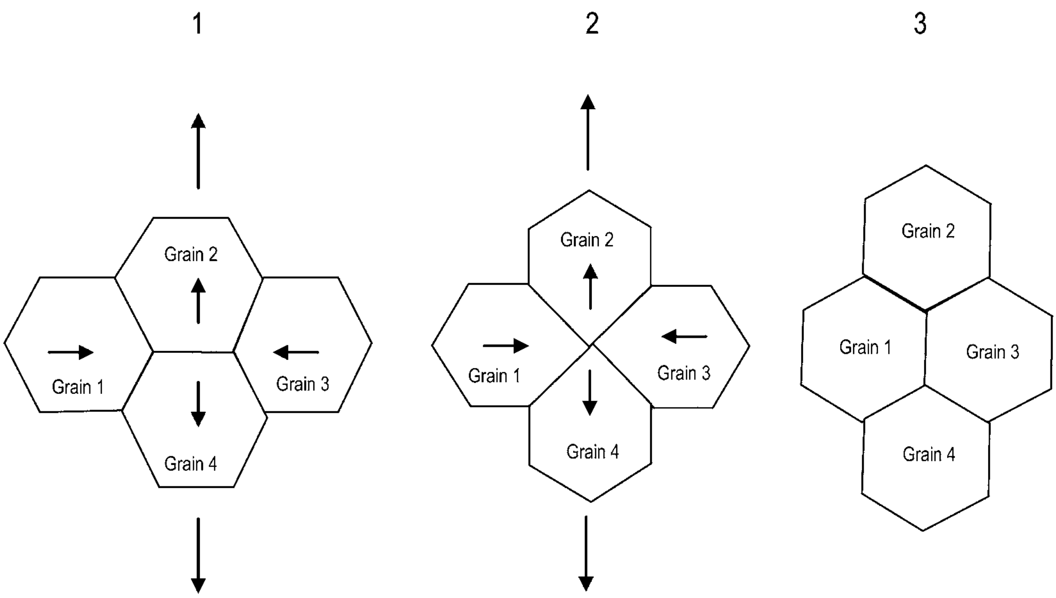

Fig. 16.27 Grain-boundary rotation. Source: Ref 13

diffusion mechanisms time to allow this rearrangement.

In the single-sheet SPF process (Fig. 16.28), a single sheet of metal is sealed around its periphery between an upper and lower die. The lower die is either machined to the desired shape of the final part or a die inset is placed in the lower die box. The dies and sheet are maintained at the SPF temperature, and gas pressure is used to form the sheet down over the tool. The lower cavity is maintained under vacuum or can be vented to the atmosphere. After the sheet is heated to its superplastic temperature range, gas pressure is injected through inlets in the upper die. This pressurizes the cavity above the metal sheet, forcing it to superplastically form to the shape of the lower die. Gas pressurization is applied slowly so that the strains in the sheet are maintained in the superplastic range, and the pressure is varied during the forming process to maintain the required slow strain rate. Typical forming cycles for aluminum alloys are 5 to 6 MPa (700 to 900 psi) at 450 to 520 °C (840 to 975 °F) and 0.7 to 1.4 MPa (100 to 200 psi) and 900 °C (1650 °F) for titanium alloys.

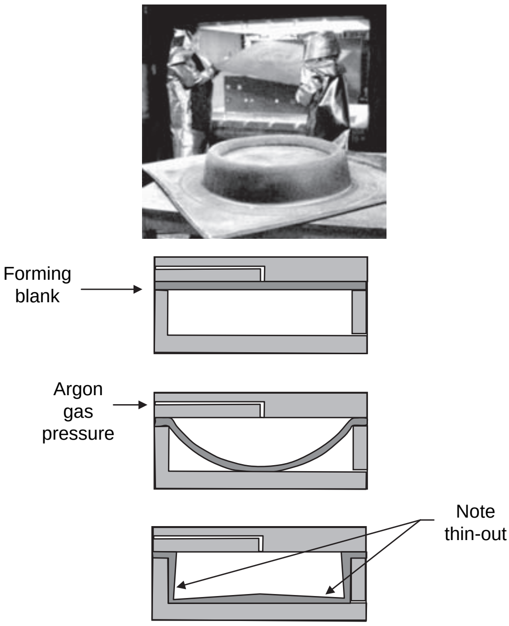

Fig. 16.28 Single-sheet superplastic forming. Source: Ref 8

In aluminum alloys, the hard particles at the grain boundaries that help control grain growth may contribute to the formation of voids, a process called cavitation. Cavitation on the order of 3% can occur after approximately 200% of superplastic deformation. Cavitation can be minimized, or eliminated, by applying a hydrostatic back pressure to the sheet during forming, as shown schematically in Fig. 16.29. Back pressures of 0.7 to 3.5 MPa (100 to 500 psi) are normally sufficient to suppress cavitation.

For titanium alloys, superplastic forming can be combined with diffusion bonding (SPF/DB) to form a one-piece unitized structure (Fig. 16.30). Titanium is very amenable to diffusion bonding because the thin, protective oxide layer (TiO_2) dissolves into the titanium above 620 °C (1150 °F), leaving a clean surface. Internal sheets of the multilayer preform are formed into integral stiffening members between the outer sheets, with geometry of the stiffening core determined by the welding patterns. Truss core, sinusoidal, egg-crate, and other internal stiffening geometries can be produced in a single forming step using automated welding patterns. Low forming pressures and single-step processing significantly reduce

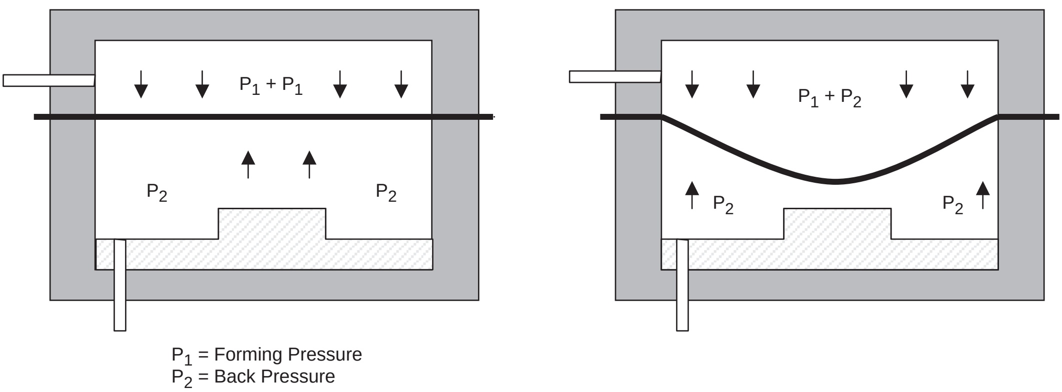

Fig. 16.29 Back pressure forming to suppress cavitation. Source: Ref 8

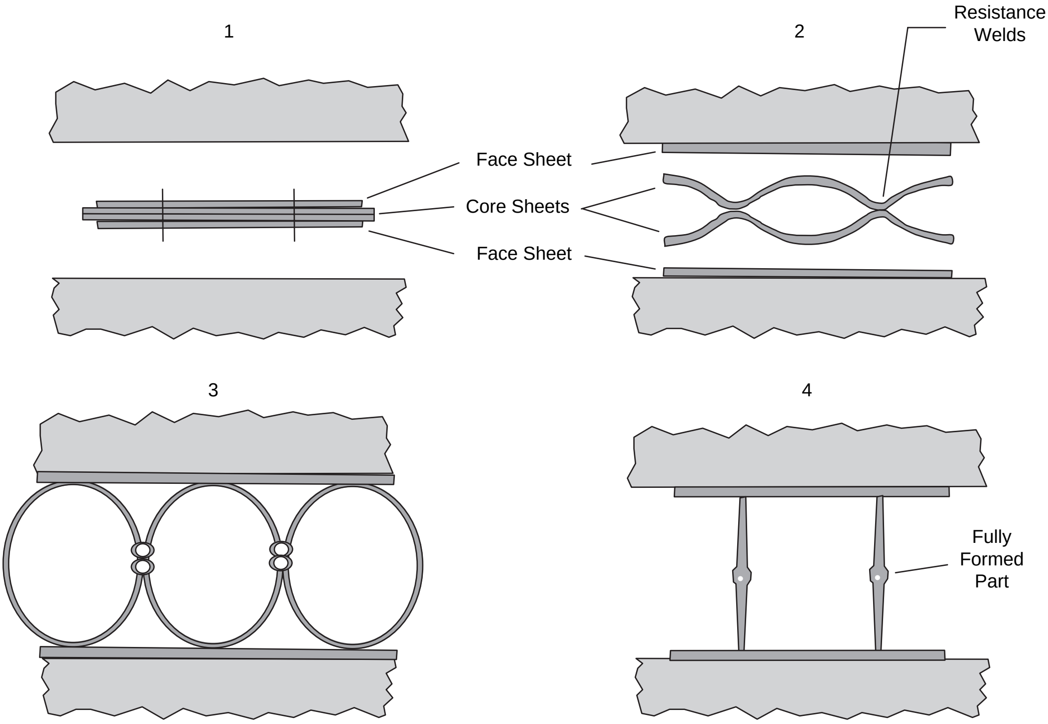

Fig. 16.30 Fabrication of part by subjecting four metal sheets to superplastic forming and diffusion bonding. Source: Ref 8

tooling costs compared to conventional methods. However, the protective aluminum oxide (Al_2O_3) coating on aluminum does not dissolve and must either be removed or ruptured to promote diffusion bonding. Although diffusion bonding of aluminum alloys has successfully been demonstrated in the laboratory, SPF/DB of aluminum alloys is not yet a commercial process.

ACKNOWLEDGMENTS

Sections of this chapter were adapted from "Flat, Bar, and Shape Rolling" by G.D. Lahoti, "Conventional Hot Extrusion," "Hydrostatic Extrusion," and "Cold Extrusion" by P.S. Raghupathi, W.C. Setzer, and M. Baxi, all in *Forging and Forming,* Volume 14, *ASM Handbook,* ASM International, 1988.

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