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Henry S. Valberg
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1 Characteristics of Metal Forming

Metal forming is one manufacturing method among many. In order to manufacture a machine component, such as a wheel suspension arm for a car, one can choose metal forming, casting, or machining as the shaping method. These three shaping methods can be considered competing processes. The method chosen will usually be the one that provides a product, with proper function and properties, at the lowest cost. In this chapter, characteristics of these three shaping methods will be described, with special emphasis on metal forming, when used to create the intended shape of a component through plastic deformations of an initial *workpiece* of simple shape.

1.1 Definition of Metal Forming

Metal forming refers to shaping of metallic materials by means of plastic deformation. The term *plastic deformation* describes permanent shape change, in contrast to *elastic deformation*. An elastic deformation disappears when the load is removed. Many industrial materials are shaped into useful products by plastic deformation. Clay is a material that is shaped by plastic deformation before it is fired to become a final useful solid ceramic material. In addition, polymer materials are commonly shaped in melted condition by means of plastic deformation. But in this book, the treatment is confined to plastic deformation of metals.

A more comprehensive definition of metal forming is the technology used for shaping metal alloys into useful products by forming processes such as rolling, forging, extrusion, drawing, and sheet-metal forming. With this definition, the term involves many scientific disciplines, including chemistry, physics, mechanics, and general manufacturing technology.

1.2 Plastic Deformations on Micro- and Macroscopic Scales

The term *plastic deformation* can be explained if one examines a metallic material that is subjected to deformation in a specific metal forming process.

Figure 1.1 shows the frictionless compression of a cylinder between two parallel platens as either a cold- or a hot-forming process. An area element from an internal

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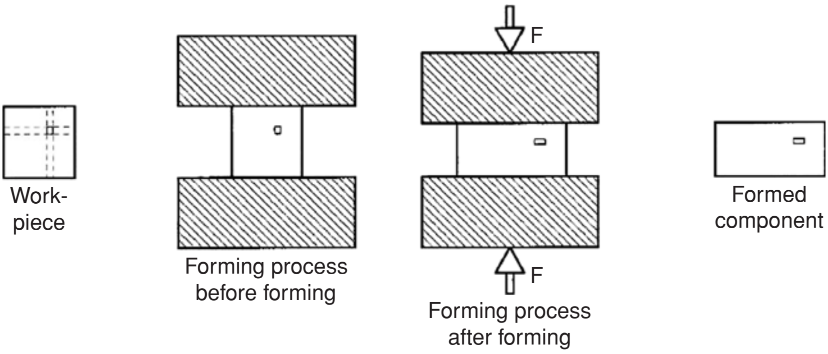

Figure 1.1. Frictionless compression of a cylinder with internal grid pattern in the horizontal midplane.

grid pattern is sketched in the axial midplane of the cylinder prior to forming. The plastic deformation of the cylinder during the test can be observed on a macro scale and quantified through the change of shape of the elements of this *grid pattern*. In Fig. 1.1 only one grid element of the pattern is shown, because all grid elements behave the same way when frictionless compression is applied. In practical cases of forming, this type of grid pattern technique is often used to map deformations inside a workpiece. As the figure illustrates, the workpiece, and the grid element inside its midsection, are compressed in the vertical direction, while they expand in the radial direction. This change of shape represents the *macroscopic deformation* of the workpiece.

In the treatment in the continuum mechanics,[1] the workpiece is considered idealized as a continuous medium, also termed a *continuum*. In such a material, the average density, for instance, will vary continuously with respect to time and position within the medium. When a volume element inside the medium is made smaller, the boundary value of this property, as the size of the element approaches zero, will then be the density in the point.

In practice a real metallic material will never be a continuum. A conventional pearlitic–ferritic C–Mn steel, for instance, will on the microscopic level be strongly inhomogeneous, as shown in Fig. 1.2(a). On examining it at sufficiently large magnification, one will see that the microstructure of the material consist of an aggregate of *ferritic* and *pearlitic* grains, with *grain boundaries* separating each grain from its neighbors. The grain boundary is known to have lower density (due to higher dislocation density) than the interior of the grain and to have mechanical properties different from those of the interior. Moreover, a pearlitic grain consists of flakes of *cementite* (Fe_3C) embedded in a matrix of ferrite. It is much harder and has much higher flow stress than a ferrite grain, which consists of pure iron with a small amount of carbon in solid solution.

If we examine a pearlite grain in more detail, we find that the flakes of cementite are extremely hard and brittle. During plastic deformation of such grains, the

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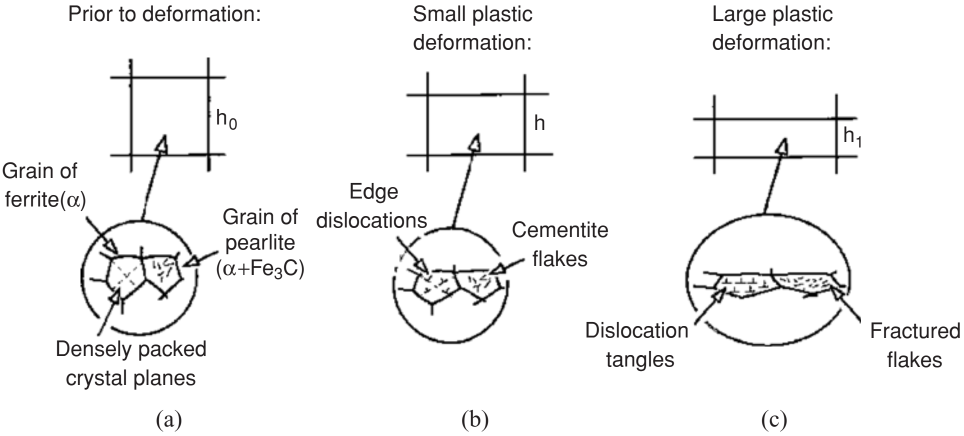

Figure 1.2. Schematic sketch showing micro-scale effects of plastic deformation in pearlitic–ferritic steel: (a) undeformed grains, (b) deformation of ferrite by dislocation movement, (c) multiplication of dislocations in ferrite and fracture of cementite flakes in pearlite.

ferrite, in which the brittle flakes are embedded, deforms severely by microscopic plastic deformation. The flakes themselves, because of their low ductility, fracture into small pieces; see Fig. 1.2(c). The reason the pearlitic grains can deform plastically without damaging the whole microstructure is the distribution of the cementite flakes as small islands in the more ductile ferrite matrix.

Cast irons, which contain much more carbon than steel ($>1.7\%$ C), sometimes can form a microstructure in which films of cementite appear as a continuous skeleton throughout the grain boundaries of the whole material. The materials in this state are very brittle and cannot be deformed plastically without fracture. If, for example, one tries to bend a component of such a material, to change its shape permanently, it will fracture before it is plasticized. This illustrates that on a micro scale a metallic material commonly consists of different phases with different mechanical properties. Moreover, most metallic materials will consist of an aggregate of crystal grains. In the grains, the atoms are packed along various crystallographic planes. The orientation of the crystal planes will be different from one grain to a neighboring grain. Because these inhomogeneities are of small size, commonly $< 100\ \mu$m, the material can, anyhow on a macroscopic level, be considered a continuum and can be well described by the theory of continuum mechanics.

When considered on a sufficiently small scale, so that atoms become visible, plastic deformation of metals is known to be caused by *dislocations*. They are generated in the metal upon plastic deformation and move through the *grains*, along the densely packed atomic planes of the microstructure, as shown in Fig. 1.2(b,c) and Fig. 1.3. New dislocations are also formed during cold forming, so that the dislocation density increases as the metal is subjected to larger strains.

However, plastic deformation in melted polymers and in clay occurs by mechanisms different from those in metals. In polymers, sliding of long polymer chains against one another is the most common mechanism of plastic deformation. In clays,

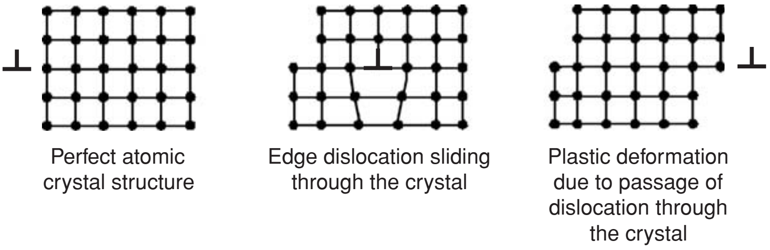

Figure 1.3. Edge dislocation sliding through a perfect crystal yields plastic deformation on the atomic level.

the *deformation mechanism* is one of small flakes of the material sliding over neighboring flakes by means of thin films of water separating the flakes.

1.3 Characteristics of Metal Forming

Following are some general characteristics of metal forming processes:

- The workpiece is completely or partially subjected to plastic deformation during the forming operation; that is, it is *plasticized*.
- The plastic deformation is most commonly large.
- Little or no material is removed during the forming process.
- The microstructure of the as-cast workpiece is broken down by the plastic deformation. Therefore, the final component, or *product*, made by metal forming usually will have better mechanical properties than a similar product manufactured by casting or machining.
- During cold deformation, mechanical properties, such as the yield strength and tensile strength, will increase because of the accumulation of plastic strain in the material.

These are typical characteristics of metal forming as a manufacturing process. The first three points mentioned are illustrated by examples in Fig. 1.4. In this figure, the material that is subjected to plastic deformation is shown as a hatched area. In these examples, material removal only occurs in the closed-die forging process, where a *flash* is formed. After forming, the flash must be removed by trimming before the finished forging can be used.

1.4 Alternatives to Metal Forming

In Fig. 1.5 and in Table 1.1, common manufacturing processes, such as forging, casting, and turning, are compared when applied for production of a specific component. As shown in the figure, metal forming can result in some material loss, for instance, in closed-die forging, in which a flash forms toward the end of the forming process.

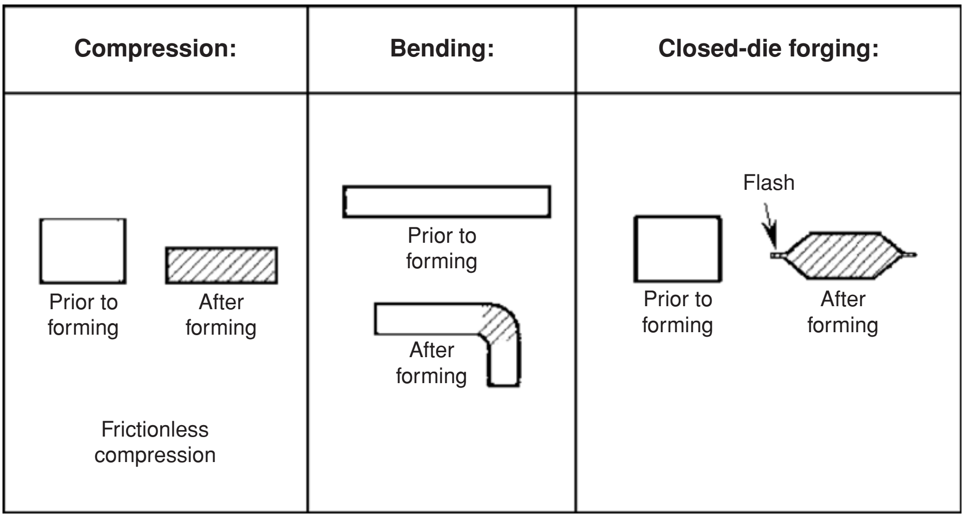

Figure 1.4. Characteristics of metal forming illustrated by different metal forming processes.

In casting, the inlet channels, consisting of *pouring cup*, *sprue*, and *runner*, represent material that is wasted. In casting, *risers* are also commonly used to feed molten metal into parts of the casting that solidify late. Without such risers, the casting would likely develop defects at these locations, such as, for instance, shrinkage cavities. The metal of a riser is commonly discarded after the casting operation and therefore represents material loss. Most commonly, however, the largest material

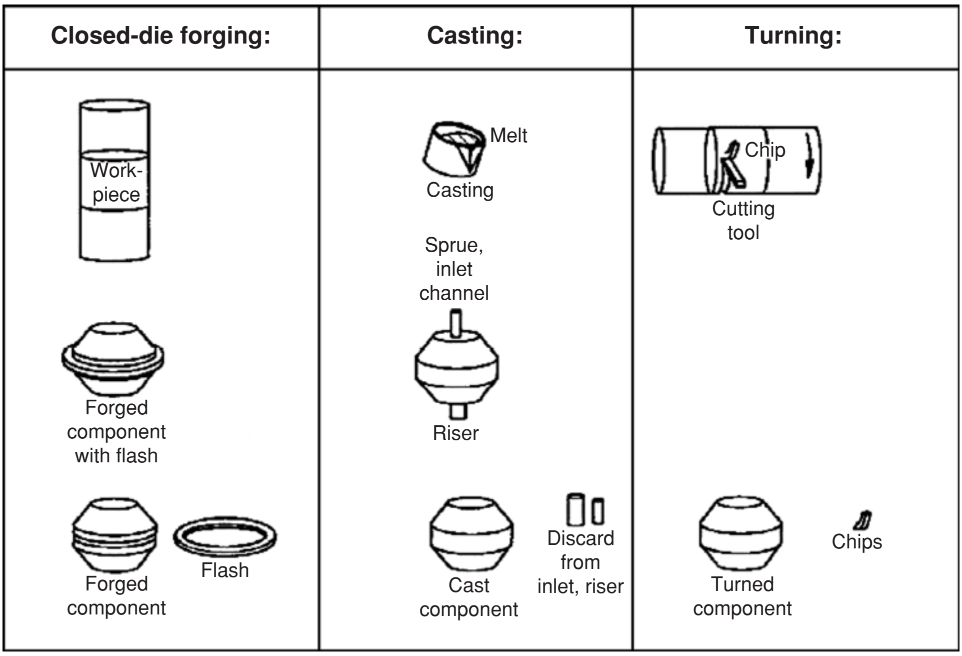

Figure 1.5. Manufacture of a massive component by means of different methods.

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Table 1.1. *Advantages (+) and disadvantages (÷) of some manufacturing methods*

Property	Closed-die forging	Casting	Turning
Necessary production equipment	÷ Complex and expensive forming machine, tooling usually expensive.	+/÷ Rather cheap equipment in sand and die casting. Complex and expensive equipment in pressure casting.	+ Turning lathe is rather complex and expensive, but tooling is rather cheap.
Freedom with respect to selection of shape of formed component	÷ Little freedom: one die gives one shape.	÷ Little freedom: one sand form or mold gives one shape.	+ Large freedom: one cutting tool produces many different shapes.
Mechanical properties of finished product	+ Improved through plastic deformation.	÷ Cast microstructure; risk of porosity or other casting defects.	÷ Same as for casting, when turning cast work material.
Loss of material	+ Little (flash and machining allowance).	+ Moderate (metal in inlet channels and risers is discarded).	÷ Usually large (formation of metal chips).
Typical component	Security detail of car, such as wheel suspension.	Door handle grip of complex shape.	Machine components produced in small numbers.

loss is experienced in metal removal processes, that is, machining processes such as turning, in which a lot of metal has to be removed to obtain the final shape.

As Table 1.1 depicts, each of the three production processes discussed here has its good and bad characteristics. When it comes to production of a component in small numbers, metal forming will usually be too expensive, and the situation is the same for pressure casting because of its high tooling costs. These processes usually demand mass production to distribute the high tooling cost over many finished components. Turning, however, because of its cheap tooling and its flexibility with regard to product shape, is commonly preferred when a component is to be produced in small numbers.

If large components are to be made, or components of intricate shape, casting is usually an attractive production process. During production of long shapes with constant cross section (e.g., strips, rod, profiles, or plates), metal forming processes such as rolling, extrusion, and drawing are most commonly applied. If there are strict requirements on the quality of the product (e.g., high strength, high resistance against fatigue, or low acceptance of internal defects), then one will usually specify that the product be made by metal forming, for instance, by hot forging. During production of security components (e.g., a steering column or a heavily loaded wheel suspension in an automobile), it is usually specified that the components should be

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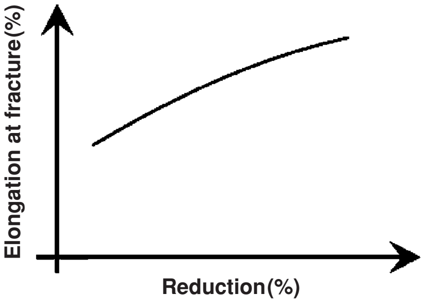


Figure 1.6. Hot working of cast metal increases its ductility because the microstructure is altered.

made by metal forming, because that ensures a component with excellent mechanical properties, such as high fatigue resistance.

If there are special demands on the finished product with regard to mechanical properties, forging may be the only acceptable manufacturing process. If not, one will in each case select the cheapest of the three mentioned candidates that gives a product of sufficient quality.

1.5 Change of Properties Due to Plastic Working

As mentioned previously, the microstructure of a casting will be broken down and refined as a result of subsequent plastic deformation. During hot forming, the working of the microstructure will improve the mechanical properties of the workpiece material, for example, by increasing its ductility; see Fig. 1.6.

If a micro-alloyed steel is hot-rolled under conditions that ensure recrystallization of the material – during or subsequent to rolling – and if the working temperature in the final passes is kept below a critical temperature (say, $< 950^\circ$C), the mechanical properties of the rolled product can be greatly improved by that thermo-mechanical treatment. The grain size of the material is then reduced during the treatment, and the resulting product will display higher yield and tensile strength, along with better ductility and toughness than in the initial cast condition. High-strength micro-alloyed steels are therefore made by means of such thermomechanical treatment.

During cold working, the mechanical strength of a metal (in terms of yield stress or ultimate tensile strength, for instance) increases with cold deformation, while the ductility decreases[2]; see Fig. 1.7. Many so-called wrought alloys are therefore used in their cold-worked and partially annealed condition. This state is characterized by a combination of rather high strength and good ductility.

The initial workpiece in metal forming, or machining, is often made by shearing or sawing off a piece of metal from a rod, a wire, or a large plate. Because these wrought products are produced by metal forming processes, such as extrusion, drawing, or rolling, they will usually have inferior properties in the short transverse direction in relation to those in the other directions, especially in the longitudinal direction. In conventional steel production, inclusions of manganese sulfide (MnS) tend to gather in planes oriented parallel to the rolling direction as illustrated in

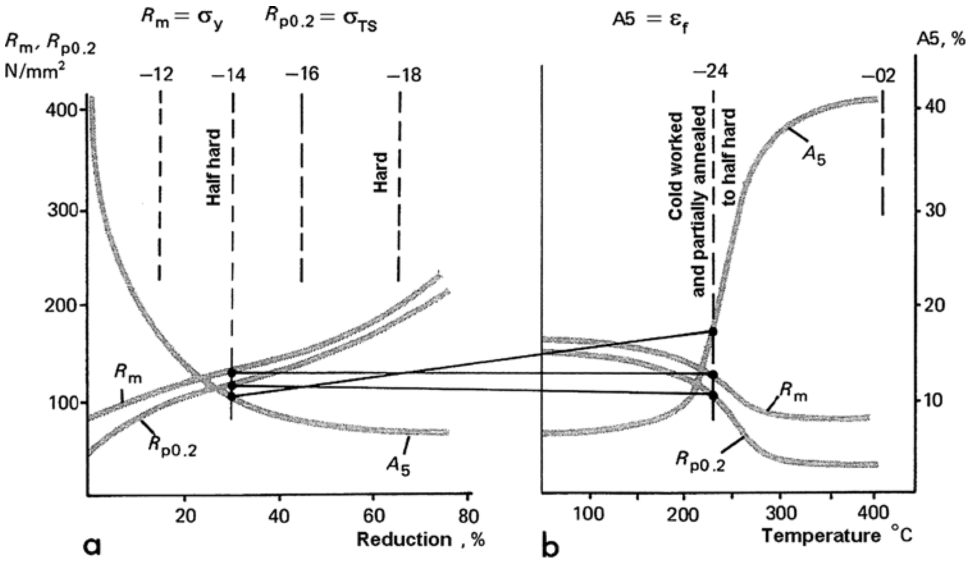


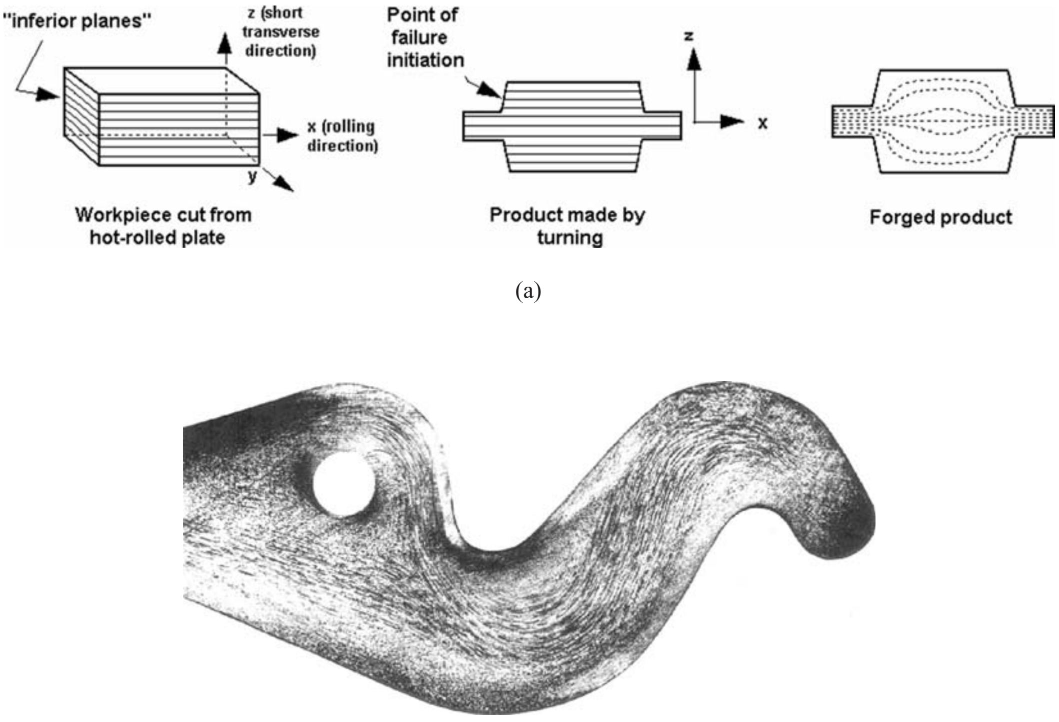
Figure 1.7. Strengthening of aluminum alloy by (a) cold working and (b) cold working followed by partial recrystallization and annealing of the aluminum alloy Al99.5. (Reproduced with due permission from SIS Förlag AB, www.sis.se.)

Fig. 1.8(a). These *enriched* planes then will have a weaker microstructure than the rest of the material. Initiation of cracks is therefore likely along these planes, and they can grow during use of the material, until a fracture occurs. The weakness of such materials in the shorter transverse direction, commonly termed the *z*-direction, is due to the presence of such weak planes.

If the component is made from a laminated plate like this by machining processes, the planes with inferior mechanical properties will remain unchanged and will extend through the outer surface layer of the machined component, on all faces of the component, except those running parallel to the initial surface of the plate; see Fig. 1.8(a). As already stated, the weak planes are sites for easy initiation of fatigue cracks, and the resulting product will have reduced fatigue strength.

However, if the component is made by a metal forming process like forging, the situation is quite different. If the forging schedule is optimized, all weak planes can be compressed and gathered to extend through the surface of the finished component, through the ring-shaped edge created when the flash is trimmed away.

The material on the edge is subjected to large plastic deformation during removal of the flash. Because of this, the finished forging will have better fatigue resistance than the corresponding machined component. This means that there is less risk that fatigue cracks will develop from these planes during regular use of the component. If such a forged component is macro-etched, the longitudinal direction of weak planes will become visible, because the microstructure will be fibrous along this direction[3]; see Fig. 1.8(b). In forging terminology, this layered appearance of the microstructure of forgings is termed *grain-flow*. If the forging schedule is



(a)

(b)

Figure 1.8. (a) Inferior material planes tend to gather in the flash in forging. (b) Macro-etched hot-forged component with good grain flow. (Reproduced with permission from Teknikföretagens Branschgrupper AB, Stockholm.)

properly set up, the component will have sound grain flow and optimum mechanical properties.

1.6 Metal Forming Processes

The variety of different metal forming processes used for industrial production is large. Because of this, it is difficult to make a simple classification system that includes all existing processes while depicting each process in relation to other manufacturing methods. However, if one limits the system to the main processes, the rather simple classification system shown in Fig. 1.9 can be made. At the highest level of this system, the manufacturing processes are divided into metal forming processes, metal removal processes, joining processes, etc. One level below, the metal forming processes are divided into two subgroups: *bulk-metal forming* and *sheet-metal forming*. This division is natural in that the problems encountered in forming of a massive body are quite different from those in sheet-metal forming. While there is mainly compressive stress in bulk-metal forming, sheet-metal forming is mainly done under high tensile stress.

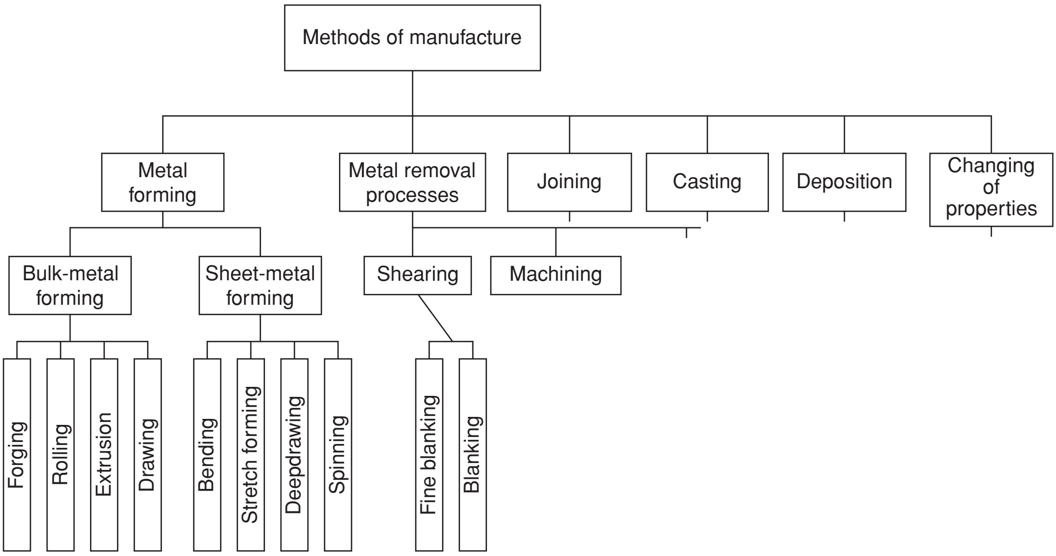


Figure 1.9. Commonly used metal forming processes classified among various manufacturing processes. Bulk-metal forming and sheet-metal forming are each divided into four subgroups.

Shearing, or cutting, is similar to metal forming in that the metal adjacent the sheared edge is subjected to plastic deformation. As a manufacturing process, shearing is often considered to be a metal removal process. At one level below, cutting is again divided into blanking, or *conventional blanking*, and *fine blanking*, according to how the shearing process is executed. Bulk-metal forming can be further divided into the four subgroups forging, rolling, extrusion, and drawing. Likewise, sheet-metal forming can be divided into bending, stretch forming, deep drawing, and spinning.

Further subdivision is also common. Forging, for instance, is divided into the two subgroups, open-die forging and closed-die forging. In the same way, extrusion can be subdivided into forward extrusion and backward extrusion.

There are similarities between the various metal forming processes. The tree structure in Fig. 1.9 can therefore be considered to be a family tree, where there are inherited similarities between the siblings at the lowest level, though at the same time there are characteristic differences. If one tries to give an overview of all metal forming processes, divided into groups and subgroups on the basis of the characteristic type of loads applied during forming, one will get a precise, but rather complex, picture. Such efforts have been carried out in the German DIN standard.[4] Because of the complexity of this system, it is not so well suited for pedagogical applications and will not be presented in full detail in this book. However, the extrusion branch of this comprehensive classification system is shown in Fig. 1.10.

At the highest level of the system, one finds metal forming as one among many other manufacturing methods. Because it is common to apply high pressure in extrusion, the process is categorized on the next level as forming under pressure. Since the