Part V Metal Forming and Sheet Metalworking

17 Fundamentals of Metal Forming

Chapter Contents

Metal forming includes a large group of manufacturing processes in which plastic deformation is used to change the shape of metal workpieces. Deformation results from the use of a tool, usually called a ***die*** in metal forming, which applies stresses that exceed the yield strength of the metal. The metal therefore deforms to take a shape determined by the geometry of the die. Metal forming dominates the class of shaping operations identified in Chapter 1 as the ***deformation processes*** (Figure 1.5).

Stresses applied to plastically deform the metal are usually compressive. However, some forming processes stretch the metal, while others bend the metal, and still others apply shear stresses to the metal. To be successfully formed, a metal must possess certain properties. Desirable properties include low yield strength and high ductility. These properties are affected by temperature. Ductility is increased and yield strength is reduced when work temperature is raised. The effect of temperature gives rise to distinctions between cold working, warm working, and hot working. Strain rate and friction are additional factors that affect performance in metal forming. All of these issues are examined in this chapter, following an overview of the metal forming processes.

17.1 Overview of Metal Forming

Metal forming processes can be classified into two basic categories: bulk deformation processes and sheet metalworking processes. These two categories are covered

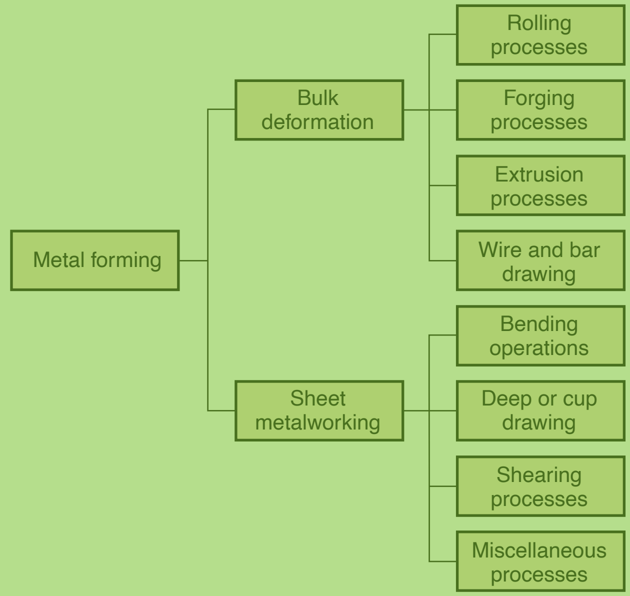

FIGURE 17.1 Classification of metal forming operations.

in detail in Chapters 18 and 19, respectively. Each category includes several major classes of shaping operations, as indicated in Figure 17.1.

Bulk Deformation Processes Bulk deformation processes are generally characterized by significant deformations and massive shape changes, and the surface area–to–volume of the work is relatively small. The term ***bulk*** describes the work parts that have this low area–to–volume ratio. Starting work shapes for these processes include cylindrical billets and rectangular bars. Figure 17.2 illustrates the following basic operations in bulk deformation:

- ***Rolling***. This is a compressive deformation process in which the thickness of a slab or plate is reduced by two opposing cylindrical tools called rolls. The rolls rotate so as to draw the work into the gap between them and squeeze it.
- ***Forging***. In forging, a workpiece is compressed between two opposing dies, so that the die shapes are imparted to the work. Forging is traditionally a hot working process, but many types of forging are performed cold.
- ***Extrusion***. This is a compression process in which the work metal is forced to flow through a die opening, thereby taking the shape of the opening as its own cross section.
- ***Drawing***. In this forming process, the diameter of a round wire or bar is reduced by pulling it through a die opening.

Sheet Metalworking Sheet metalworking processes are forming and cutting operations performed on metal sheets, strips, and coils. The surface area–to–volume ratio of the starting metal is high; thus, this ratio is a useful means to distinguish bulk deformation from sheet metal processes. ***Pressworking*** is the term often applied to sheet metal operations because the machines used to perform these operations are

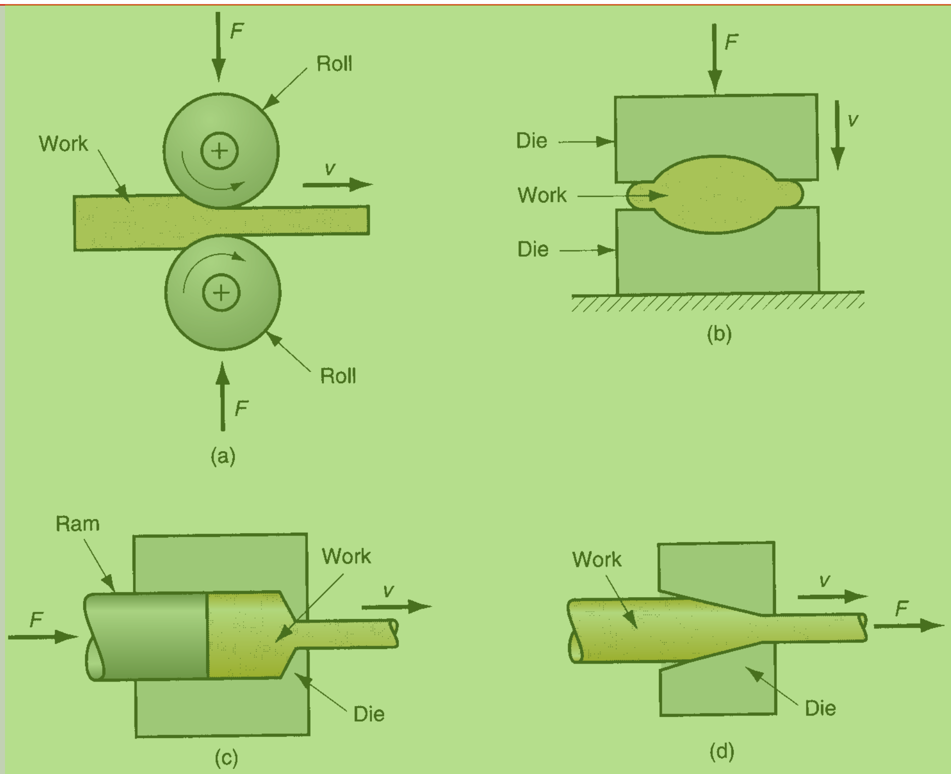

FIGURE 17.2 Basic bulk deformation processes: (a) rolling, (b) forging, (c) extrusion, and (d) drawing. Relative motion in the operations is indicated by *v*; forces are indicated by *F*.

presses (presses of various types are also used in other manufacturing processes). A part produced in a sheet metal operation is often called a ***stamping***.

Sheet metal operations are always performed as cold working processes and are usually accomplished using a set of tools called a ***punch*** and ***die***. The punch is the positive portion and the die is the negative portion of the tool set. The basic sheet metal operations are sketched in Figure 17.3 and are defined as follows:

- ***Bending.*** Bending involves straining of a metal sheet or plate to take an angle along a (usually) straight axis.
- ***Drawing.*** In sheet metalworking, drawing refers to the forming of a flat metal sheet into a hollow or concave shape, such as a cup, by stretching the metal. A blankholder is used to hold down the blank while the punch pushes into the sheet metal, as shown in Figure 17.3(b). To distinguish this operation from bar and wire drawing, the terms ***cup drawing*** or ***deep drawing*** are often used.
- ***Shearing.*** This process seems somewhat out-of-place in a list of deformation processes, because it involves cutting rather than forming. A shearing operation cuts the work using a punch and die, as in Figure 17.3(c). Although it is not a forming process, it is included here because it is a necessary and very common operation in sheet metalworking.

The miscellaneous processes within the sheet metalworking classification in Figure 17.1 include a variety of related shaping processes that do not use punch and die tooling. Examples of these processes are stretch forming, roll bending, spinning, and bending of tube stock.

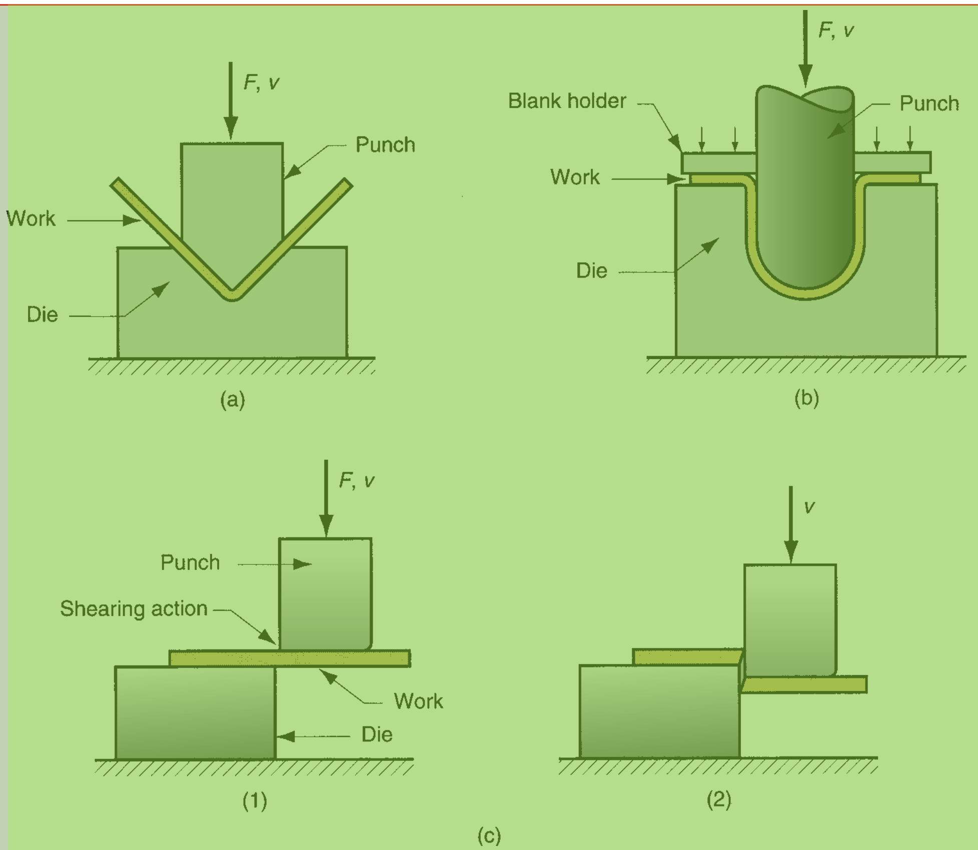

FIGURE 17.3 Basic sheet metalworking operations: (a) bending, (b) drawing, and (c) shearing: (1) as punch first contacts sheet, and (2) after cutting. Force and relative motion in these operations are indicated by F and v.

17.2 Material Behavior in Metal Forming

Considerable insight about the behavior of metals during forming can be obtained from the stress–strain curve. The typical stress–strain curve for most metals is divided into an elastic region and a plastic region (Section 3.1.1). In metal forming, the plastic region is of primary interest because the material is plastically and permanently deformed in these processes.

The typical stress–strain relationship for a metal exhibits elasticity below the yield point and strain hardening above it. Figures 3.4 and 3.5 indicate this behavior in linear and logarithmic axes. In the plastic region, the metal's behavior is expressed by the flow curve:

$$\sigma = K\epsilon^n$$

where K = the strength coefficient, MPa (lb/in^2); and n is the strain hardening exponent. The stress σ and strain ϵ in the flow curve are true stress and true strain. The flow curve is generally valid as a relationship that defines a metal's plastic behavior in cold working. Typical values of K and n for different metals at room temperature are listed in Table 3.4.

Flow Stress The flow curve describes the stress–strain relationship in the region in which metal forming takes place. It indicates the flow stress of the metal—the strength property that determines forces and power required to accomplish a particular forming operation. For most metals at room temperature, the stress–strain plot of Figure 3.5 indicates that as the metal is deformed, its strength increases due to strain hardening. The stress required to continue deformation must be increased to match this increase in strength. ***Flow stress*** is defined as the instantaneous value of stress required to continue deforming the material—to keep the metal "flowing." It is the yield strength of the metal as a function of strain, which can be expressed:

$$Y_f = K\epsilon^n \tag{17.1}$$

where Y_f = flow stress, MPa (lb/in²).

In the individual forming operations discussed in the following two chapters, the instantaneous flow stress can be used to analyze the process as it is occurring. For example, in certain forging operations, the instantaneous force during compression can be determined from the flow stress value. Maximum force can be calculated based on the flow stress that results from the final strain at the end of the forging stroke.

In other cases, the analysis is based on the average stresses and strains that occur during deformation rather than instantaneous values. Extrusion represents this case, Figure 17.2(c). As the billet is reduced in cross section to pass through the extrusion die opening, the metal gradually strain hardens to reach a maximum value. Rather than determine a sequence of instantaneous stress–strain values during the reduction, which would be not only difficult but also of limited interest, it is more useful to analyze the process based on the average flow stress during deformation.

Average Flow Stress The average flow stress (also called the ***mean flow stress***) is the average value of stress over the stress–strain curve from the beginning of strain to the final (maximum) value that occurs during deformation. The value is illustrated in the stress–strain plot of Figure 17.4. The average flow stress is determined by integrating the flow curve equation, Equation (17.1), between zero and the final strain value defining the range of interest. This yields the equation:

$$\bar{Y}_f = \frac{K\epsilon^n}{1+n} \tag{17.2}$$

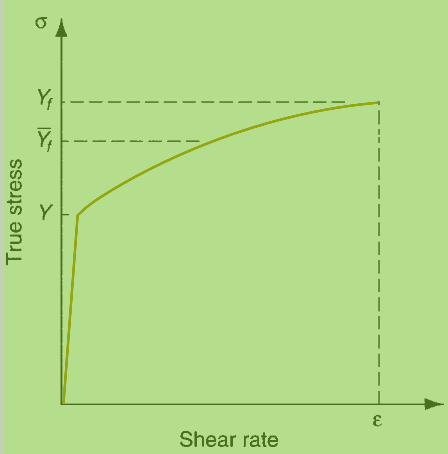

FIGURE 17.4 Stress–strain curve indicating location of average flow stress $\bar{Y}_f$ in relation to yield strength Y and final flow stress Y_f.

where $\overline{Y}_f$ = average flow stress, MPa (lb/in^2); and ϵ = maximum strain value during the deformation process.

Extensive use is made of the average flow stress in the study of the bulk deformation processes in the following chapter. Given values of K and n for the work material, a method of computing final strain will be developed for each process. Based on this strain, Equation (17.2) can be used to determine the average flow stress to which the metal is subjected during the operation.

3 Temperature in Metal Forming

The flow curve is a valid representation of stress–strain behavior of a metal during plastic deformation, particularly for cold working operations. For any metal, the values of K and n depend on temperature. Strength and strain hardening are both reduced at higher temperatures. These property changes are important because they result in lower forces and power during forming. In addition, ductility is increased at higher temperatures, which allows greater plastic deformation of the work metal. Three temperature ranges used in metal forming can be distinguished: cold, warm, and hot working.

Cold Working Cold working (also known as ***cold forming***) is metal forming performed at room temperature or slightly above. Significant advantages of cold forming compared to hot working are (1) greater accuracy, meaning closer tolerances can be achieved; (2) better surface finish; (3) higher strength and hardness of the part due to strain hardening; (4) grain flow during deformation provides the opportunity for desirable directional properties to be obtained in the resulting product; and (5) no heating of the work is required, which saves on furnace and fuel costs and permits higher production rates. Owing to this combination of advantages, many cold forming processes have become important mass-production operations. They provide close tolerances and good surfaces, minimizing the amount of machining required so that these operations can be classified as net shape or near net shape processes (Section 1.3.1).

There are certain disadvantages or limitations associated with cold forming operations: (1) higher forces and power are required to perform the operation; (2) care must be taken to ensure that the surfaces of the starting workpiece are free of scale and dirt; and (3) ductility and strain hardening of the work metal limit the amount of forming that can be done to the part. In some operations, the metal must be annealed (Section 26.1) in order to allow further deformation to be accomplished. In other cases, the metal is simply not ductile enough to be cold worked.

To overcome the strain hardening problem and reduce force and power requirements, many forming operations are performed at elevated temperatures. There are two elevated temperature ranges involved, giving rise to the terms warm working and hot working.

Warm Working Because plastic deformation properties are normally enhanced by increasing workpiece temperature, forming operations are sometimes performed at temperatures somewhat above room temperature but below the recrystallization temperature. The term ***warm working*** is applied to this second temperature range. The dividing line between cold working and warm working is often expressed in terms of the melting point for the metal. The dividing line is usually taken to be $0.3T_m$, where T_m is the melting point (absolute temperature) for the particular metal.

The lower strength and strain hardening at the intermediate temperatures, as well as higher ductility, provide warm working with the following advantages over cold working: (1) lower forces and power, (2) more intricate work geometries possible, and (3) need for annealing may be reduced or eliminated.

Hot Working Hot working (also called ***hot forming***) involves deformation at temperatures above the recrystallization temperature (Section 3.3). The recrystallization temperature for a given metal is about one-half of its melting point on the absolute scale. In practice, hot working is usually carried out at temperatures somewhat above $0.5T_m$. The work metal continues to soften as temperature is increased beyond $0.5T_m$, thus enhancing the advantage of hot working above this level. However, the deformation process itself generates heat, which increases work temperatures in localized regions of the part. This can cause melting in these regions, which is highly undesirable. Also, scale on the work surface is accelerated at higher temperatures. Accordingly, hot working temperatures are usually maintained within the range $0.5T_m$ to $0.75T_m$.

The most significant advantage of hot working is the capability to produce substantial plastic deformation of the metal—far more than is possible with cold working or warm working. The principal reason for this is that the flow curve of the hot-worked metal has a strength coefficient that is substantially less than at room temperature, the strain hardening exponent is zero (at least theoretically), and the ductility of the metal is significantly increased. All of this results in the following advantages relative to cold working: (1) the shape of the work part can be significantly altered, (2) lower forces and power are required to deform the metal, (3) metals that usually fracture in cold working can be hot formed, (4) strength properties are generally isotropic because of the absence of the oriented grain structure typically created in cold working, and (5) no strengthening of the part occurs from work hardening. This last advantage may seem inconsistent, since strengthening of the metal is often considered an advantage for cold working. However, there are applications in which it is undesirable for the metal to be work hardened because it reduces ductility, for example, if the part is to be subsequently processed by cold forming. Disadvantages of hot working include (1) lower dimensional accuracy, (2) higher total energy required (due to the thermal energy to heat the workpiece), (3) work surface oxidation (scale), (4) poorer surface finish, and (5) shorter tool life.

Recrystallization of the metal in hot working involves atomic diffusion, which is a time-dependent process. Metal forming operations are often performed at high speeds that do not allow sufficient time for complete recrystallization of the grain structure during the deformation cycle itself. However, because of the high temperatures, recrystallization eventually does occur. It may occur immediately following the forming process or later, as the workpiece cools. Even though recrystallization may occur after the actual deformation, its eventual occurrence, and the substantial softening of the metal at high temperatures, are the features that distinguish hot working from warm working or cold working.

Isothermal Forming Certain metals, such as highly alloyed steels, many titanium alloys, and high-temperature nickel alloys, possess good hot hardness, a property that makes them useful for high-temperature service. However, this very property that makes them attractive in these applications also makes them difficult to form with conventional methods. The problem is that when these metals are heated to their hot working temperatures and then come in contact with the relatively cold forming tools, heat is quickly transferred away from the part surfaces, thus raising the strength in these regions. The variations in temperature and strength in different regions of the workpiece cause irregular flow patterns in the metal during deformation, leading to high residual stresses and possible surface cracking.

Isothermal forming refers to forming operations that are carried out in such a way as to eliminate surface cooling and the resulting thermal gradients in the work part. It is accomplished by preheating the tools that come in contact with the part to the same temperature as the work metal. This weakens the tools and reduces tool life, but it avoids the problems described above when these difficult metals are formed by conventional methods. In some cases, isothermal forming represents the only way in which these work materials can be formed. The procedure is most closely associated with forging, and isothermal forging is discussed in the following chapter.

17.4 Strain Rate Sensitivity

Theoretically, a metal in hot working behaves like a perfectly plastic material, with strain hardening exponent $n = 0$. This means that the metal should continue to flow under the same level of flow stress, once that stress level is reached. However, there is an additional phenomenon that characterizes the behavior of metals during deformation, especially at the elevated temperatures of hot working. That phenomenon is strain rate sensitivity. Discussion of this topic begins with a definition of strain rate.

The rate at which the metal is strained in a forming process is directly related to the speed of deformation v. In many forming operations, deformation speed is equal to the velocity of the ram or other moving element of the equipment. It is most easily visualized in a tensile test as the velocity of the testing machine head relative to its fixed base. Given the deformation speed, ***strain rate*** is defined:

$$\dot{\epsilon} = \frac{v}{h} \tag{17.3}$$

where $\dot{\epsilon}$ = true strain rate, m/s/m (in/sec/in), or simply s^{-1}; and h = instantaneous height of the workpiece being deformed, m (in). If deformation speed v is constant during the operation, strain rate will change as h changes. In most practical forming operations, valuation of strain rate is complicated by the geometry of the work part and variations in strain rate in different regions of the part. Strain rate can reach 1000 s^{-1} or more for some metal forming processes such as high-speed rolling and forging.

It has already been observed that the flow stress of a metal is a function of temperature. At the temperatures of hot working, flow stress depends on strain rate. The effect of strain rate on strength properties is known as ***strain rate sensitivity***. The effect can be seen in Figure 17.5. As strain rate is increased, resistance to deformation increases. This usually plots approximately as a straight line on a log–log graph, thus leading to the relationship:

$$Y_f = C\dot{\epsilon}^m \tag{17.4}$$

where C is the strength constant (similar but not equal to the strength coefficient in the flow curve equation), and m is the strain rate sensitivity exponent. The value of C is determined at a strain rate of 1.0, and m is the slope of the curve in Figure 17.5(b).

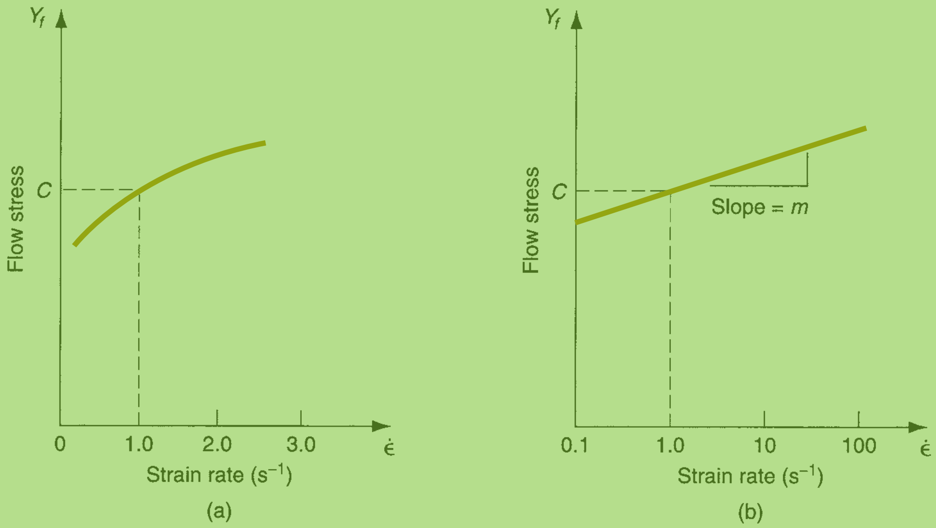

FIGURE 17.5 (a) Effect of strain rate on flow stress at an elevated work temperature. (b) Same relationship plotted on log–log coordinates.

The effect of temperature on the parameters of Equation (17.4) is pronounced. Increasing temperature decreases the value of C (consistent with its effect on K in the flow curve equation) and increases the value of m. The general result can be seen in Figure 17.6. At room temperature, the effect of strain rate is almost negligible, indicating that the flow curve is a good representation of the material behavior. As temperature is increased, strain rate plays a more important role in determining flow stress, as indicated by the steeper slopes of the strain rate relationships. This is important in hot working because deformation resistance of the material increases so dramatically as strain rate is increased. To give a sense of the effect, typical values of m for the three temperature ranges of metal working are given in Table 17.1.

Thus, even in cold working, strain rate can have an effect, if small, on flow stress. In hot working, the effect can be significant. A more complete expression for flow stress as a function of both strain and strain rate would be the following:

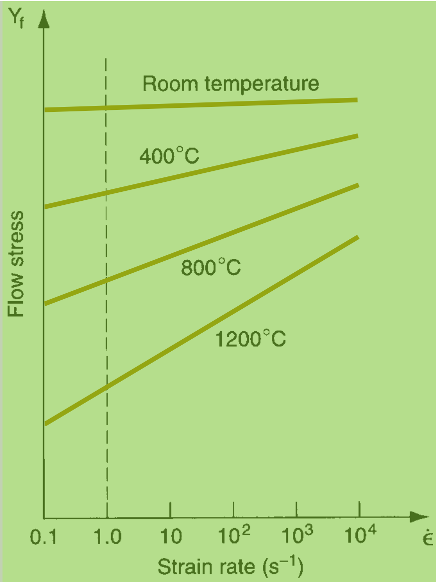

FIGURE 17.6 Effect of temperature on flow stress for a typical metal. The constant C in Equation (17.4), indicated by the intersection of each plot with the vertical dashed line at strain rate = 1.0, decreases, and m (slope of each plot) increases with increasing temperature.

TABLE • 17.1 Typical values of temperature, strain-rate sensitivity, and coefficient of friction in cold, warm, and hot working.

Category	Temperature Range	Strain-Rate Sensitivity Exponent	Coefficient of Friction
Cold working	$\leq 0.3T_m$	$0 \leq m \leq 0.05$	0.1
Warm working	$0.3T_m$–$0.5T_m$	$0.05 \leq m \leq 0.1$	0.2
Hot working	$0.5T_m$–$0.75T_m$	$0.05 \leq m \leq 0.4$	0.4–0.5

$$Y_f = A\epsilon^n\dot{\epsilon}^m \tag{17.5}$$

where A = a strength coefficient, combining the effects of the previous K and C values. Of course, A, n, and m would all be functions of temperature, and the enormous task of testing and compiling the values of these parameters for different metals and various temperatures would be forbidding.

In the coverage of the bulk deformation processes in Chapter 18, many of which are performed hot, the effect of strain rate is neglected in analyzing forces and power. For cold working and warm working, and for hot working operations at relatively low deformation speeds, this neglect represents a reasonable assumption.

5 Friction and Lubrication in Metal Forming

Friction in metal forming arises because of the close contact between the tool and work surfaces and the high pressures that drive the surfaces together in these operations. In most metal forming processes, friction is undesirable for the following reasons: (1) metal flow in the work is retarded, causing residual stresses and sometimes defects in the product; (2) forces and power to perform the operation are increased, and (3) tool wear can lead to loss of dimensional accuracy, resulting in defective parts and requiring replacement of the tooling. Since tools in metal forming are generally expensive, tool wear is a major concern. Friction and tool wear are more severe in hot working because of the much harsher environment.

Friction in metal forming is different from that encountered in most mechanical systems, such as gear trains, shafts and bearings, and other components involving relative motion between surfaces. These other cases are generally characterized by low contact pressures, low to moderate temperatures, and ample lubrication to minimize metal-to-metal contact. By contrast, the metal forming environment features high pressures between a hardened tool and a soft work part, plastic deformation of the softer material, and high temperatures (at least in hot working). These conditions can result in relatively high coefficients of friction in metal working, even in the presence of lubricants. Typical values of coefficient of friction for the three categories of metal forming are listed in Table 17.1.

If the coefficient of friction becomes large enough, a condition known as sticking occurs. ***Sticking*** in metalworking (also called ***sticking friction***) is the tendency for the two surfaces in relative motion to adhere to each other rather than slide. It means that the friction stress between the surfaces exceeds the shear flow stress of the work metal, thus causing the metal to deform by a shear process beneath the surface rather than slip at the surface. Sticking occurs in metal forming operations and is a prominent problem in rolling; it is discussed in that context in the following chapter.

Metalworking lubricants are applied to the tool—work interface in many forming operations to reduce the harmful effects of friction. Benefits include reduced sticking, forces, power, and tool wear; and better surface finish on the product. Lubricants also serve other functions, such as removing heat from the tooling. Considerations in choosing an appropriate metalworking lubricant include (1) type of forming process (rolling, forging, sheet metal drawing, and so on), (2) whether used in hot working or cold working, (3) work material, (4) chemical reactivity with the tool and work metals (it is generally desirable for the lubricant to adhere to the surfaces to be most effective in reducing friction), (5) ease of application, (6) toxicity, (7) flammability, and (8) cost.

Lubricants used for cold working operations include [4], [7] mineral oils, fats and fatty oils, water-based emulsions, soaps, and other coatings. Hot working is sometimes performed dry for certain operations and materials (e.g., hot rolling of steel and extrusion of aluminum). When lubricants are used in hot working, they include mineral oils, graphite, and glass. Molten glass becomes an effective lubricant for hot extrusion of steel alloys. Graphite contained in water or mineral oil is a common lubricant for hot forging of various work materials. More detailed treatments of lubricants in metalworking are found in references [7] and [9].

References

[1] Altan, T., Oh, S.-I., and Gegel, H. L. ***Metal Forming: Fundamentals and Applications***. ASM International, Materials Park, Ohio, 1983.

[2] Cook, N. H. ***Manufacturing Analysis***. Addison-Wesley, Reading, Massachusetts, 1966.

[3] Hosford, W. F., and Caddell, R. M. ***Metal Forming: Mechanics and Metallurgy***, 3rd ed. Cambridge University Press, Cambridge, U. K., 2007.

[4] Lange, K. ***Handbook of Metal Forming***. Society of Manufacturing Engineers, Dearborn, Michigan, 2006.

[5] Lenard, J. G. ***Metal Forming Science and Practice***, Elsevier Science, Amsterdam, The Netherlands, 2002.

[6] Mielnik, E. M. ***Metalworking Science and Engineering***. McGraw-Hill, New York, 1991.

[7] Nachtman, E. S., and Kalpakjian, S. ***Lubricants and Lubrication in Metalworking Operations***. Marcel Dekker, New York, 1985.

[8] Wagoner, R. H., and Chenot, J.-L. ***Fundamentals of Metal Forming***. John Wiley & Sons, New York, 1997.

[9] Wick, C., Benedict, J. T., and Veilleux, R. F., (eds.). ***Tool and Manufacturing Engineers Handbook***, 4th ed. Vol. II, ***Forming***. Society of Manufacturing Engineers, Dearborn, Michigan, 1984.

Review Questions

17.1 What are the differences between bulk deformation processes and sheet metal processes?

17.2 Extrusion is a fundamental shaping process. Describe it.

17.3 Why is the term pressworking often used for sheet metal processes?

17.4 What is the difference between deep drawing and bar drawing?

17.5 Indicate the mathematical equation for the flow curve.

17.6 How does increasing temperature affect the parameters in the flow curve equation?