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. 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 [true-stress-strain and true-stress-strain on log-log-scale] indicate this behavior in linear and logarithmic axes. In the plastic region, the metal's behavior is expressed by the flow curve:

$$\sigma = K\varepsilon^n$$

Where K = the strength coefficient, MPa; and *n* is the strain-hardening exponent. The stress and strain 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.

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 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 in this way:

$$Y_f = K\varepsilon^n$$

Where Y_f = flow stress, MPa.

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 [shown below].

The average flow stress is determined by integrating the flow curve equation, Eq. $Y_f = K\varepsilon^n$ between zero and the final strain value defining the range of interest. This yields the equation:

$$\bar{Y}_f = \frac{K\varepsilon^n}{1+n}$$

Where $\bar{Y}_f$ = average flow stress, MPa; and ε = maximum strain value during the deformation process.

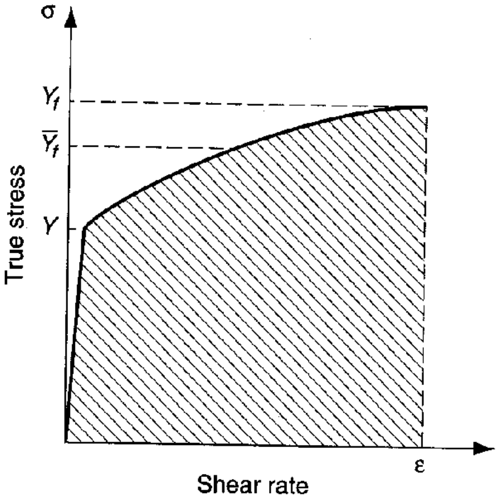


FIGURE: Stress-strain curve indicating location of average flow stress $\bar{Y}_f$ in relation to yield strength Y and final flow stress Y_f.

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. Both strength and strain hardening are reduced at higher temperatures. In addition ductility is increased at higher temperatures. These changes are important because any deformation operation can be accomplished with lower forces and power at elevated temperature. There are three temperature ranges: 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) better accuracy, meaning closer tolerances; (2) better surface finish; (3) strain hardening increases strength and hardness of the part; (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 to be achieved. Owing to this combination of advantages, many cold forming processes have developed into important mass-production operations. They provide close tolerances and good surfaces, minimizing the amount of machining required and permitting these operations to be classified as net shape or near net shape processes.

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 work piece 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 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 work piece 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 0.3 T_m, where T_m is the melting point (absolute temperature) for the particular metal.

The lower strength and strain hardening, as well as higher ductility of the metal at the intermediate temperatures, 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.** 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 0.5 T_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 lower dimensional accuracy, higher total energy required (due to the thermal energy to heat the work piece), work surface oxidation (scale), poorer surface finish, and 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 work piece cools. Even if recrystallization occurs after the actual deformation, its eventual occurrence-together with the substantial softening of the metal at high temperatures-distinguishes hot working from warm working or cold working.

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.** Let us begin our discussion of this topic by defining 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:

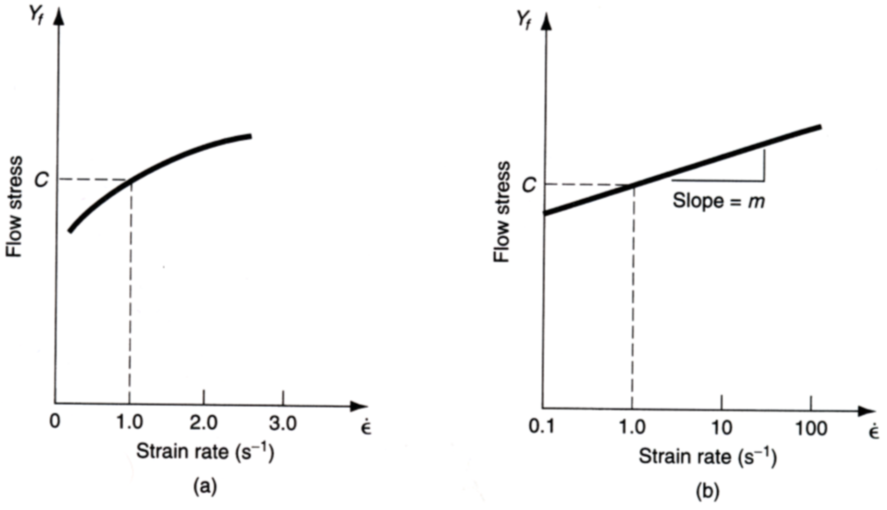
$$\dot{\varepsilon} = \frac{v}{h}$$

Where $\dot{\varepsilon}$ = true strain rate, m/s/m, or simply s^{-1} and h = instantaneous height of the work piece being deformed, m. 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.

We have already 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. 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:

$$Y_f = C\,\dot{\varepsilon}^{m} \qquad [4]$$

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 (b).



(a) Effect of strain rate on flow stress at in elevated work temperature. (b) Same relationship plotted on log-log coordinates

The effect of temperature on the parameters of Eq. (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 [shown below]. 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.

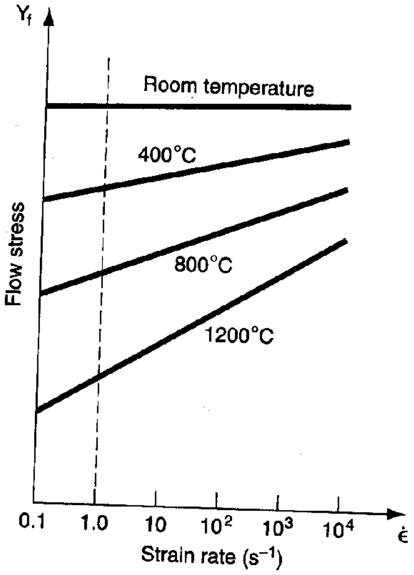


FIGURE: Effect of temperature on flow stress for a typical metal. The constant C in Eq.(4), indicated by the intersection of each plot with the vertical dashed line at strain rate = 1.0, decreases, and m (slope of each plot) increases with increasing temperature.

Rolling is the process of reducing the thickness or changing the cross-section of a long workpiece by compressive forces applied through a set of rolls (Fig.), similar to rolling dough with a rolling pin to reduce its thickness. Rolling, which accounts for about 90 percent of all metals produced by metalworking processes, was first developed in the late 1500s. The basic operation is flat rolling, or simply rolling, where the rolled products are flat plate and sheet.

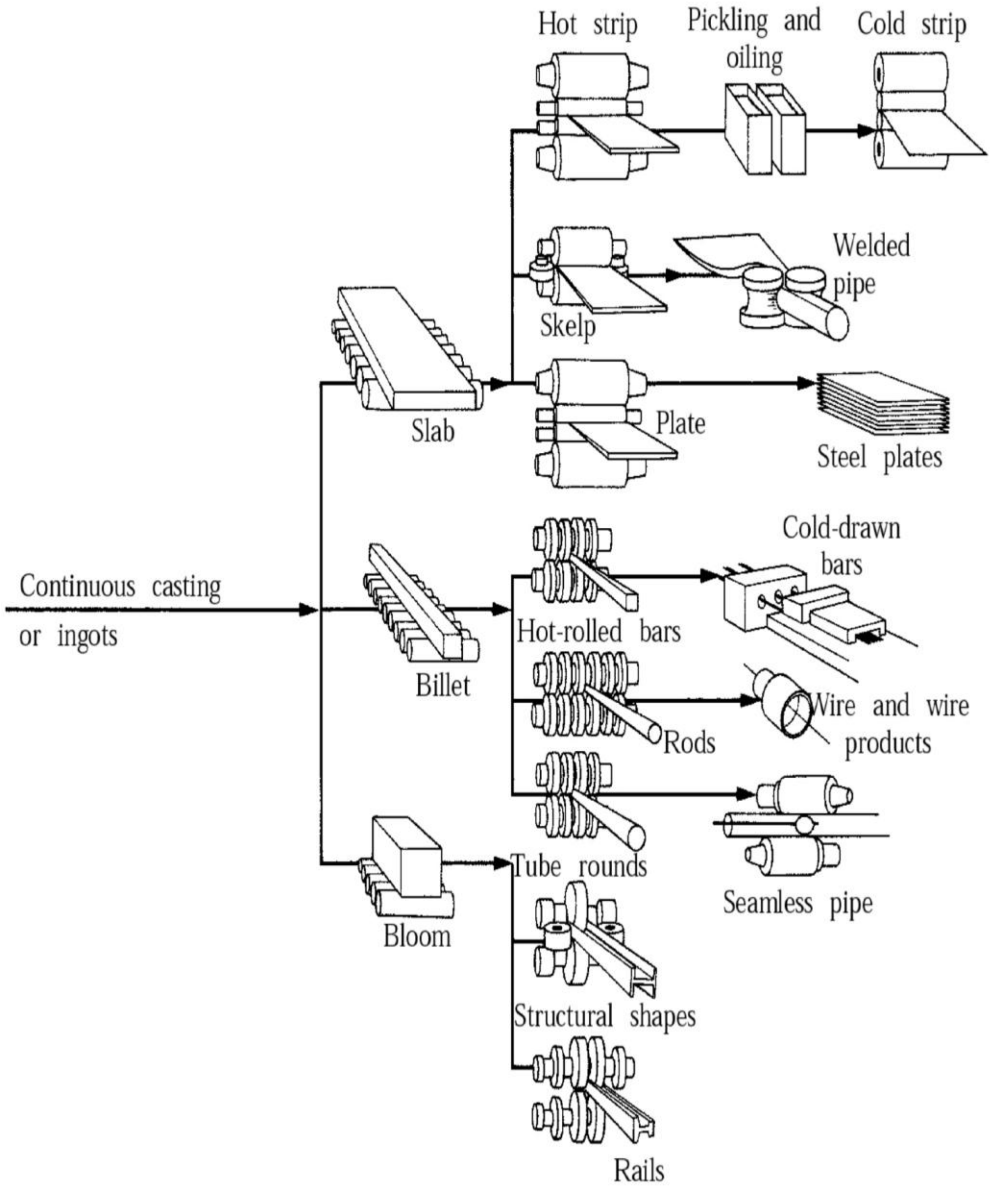


Figure: Schematic outline of various flat- and shape-rolling processes.
Source: American Iron and Steel Institute.

Plates, which are generally regarded as having a thickness greater than 6 mm, are used for structural applications **such as ship hulls, boilers, bridges, girders, machine structures, and**

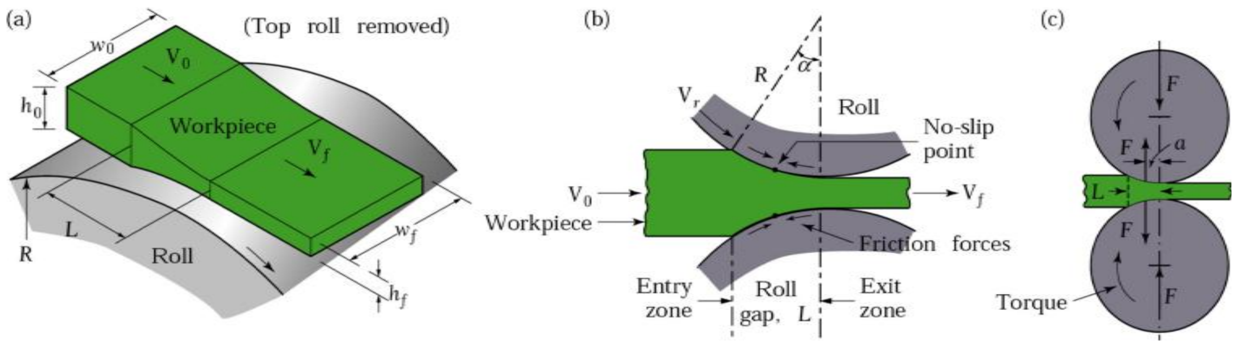
nuclear vessels. Plates can be as much as 0.3 m thick for the supports for large boilers, 150 mm for reactor vessels, and 100-125 mm for battleships and tanks.

Sheets are generally less than 6 mm thick and are **used for automobile bodies, appliances, containers for food and beverages, and kitchen and office equipment.**

Commercial aircraft fuselages are usually made of a minimum of 1 mm thick aluminum-alloy sheet. For example, skin thickness of a Boeing 747 is 1.8 mm and for the Lockheed Ll0ll it is 1.9 mm. Aluminum beverage cans are now made from sheets 0.28 mm in thickness, reduced to a final can wall thickness of 0.1 mm. Aluminum foil used to wrap candy has a thickness of 0.008 mm. Sheets are provided to manufacturing facilities as flat pieces or as strip in coils for further processing into products.

Flat Rolling

A schematic illustration of the flat rolling process is shown in Fig. a. A strip of thickness h_o enters the roll gap and is reduced to h_f by a pair of rotating rolls, each roll being powered through its own shaft by electric motors. The surface speed of the roll is V_r. The velocity of the strip increases from its initial value of V_o as it moves through the roll gap, just as fluid flows faster as it moves through a converging channel. The velocity of the strip is highest at the exit of the roll gap and is denoted as V_f. Since the surface speed of the roll is constant, there is relative sliding between the roll and the strip along the arc of contact in the roll gap L. At one point along the contact length, the velocity of the strip is the same as that of the roll. **This is called the neutral, or no slip, point. To the left of this point, the roll moves faster than the strip, and to the right of this point, the strip moves faster than the roll.** Hence the frictional forces, which oppose motion, act on the strip as shown in Fig. b.



Frictional forces

The rolls pull the material into the roll gap through a net frictional force on the material. You can see that this net frictional force must be to the right in Fig. b, and consequently the frictional force on the left of the neutral point must be higher than the force on the right.

As you can see, friction is needed to roll materials. However, energy is dissipated in overcoming friction, so increasing friction means increasing forces and power consumption. Furthermore, high friction could damage the surface of the rolled product.

Flat Rolling and Its Analysis

Flat rolling is illustrated in Figures. It involves the rolling of slabs, strips, sheets, and plates-work parts of rectangular cross-section in which the width is greater than the thickness. In flat rolling, the work is squeezed between two rolls so that its thickness is reduced by an amount called the **draft**:

$$d = h_o - h_f \qquad (1)$$

Where d = draft, mm; h_o = starting thickness, mm; and h_f = final thickness, mm. Draft is sometimes expressed as a fraction of the starting stock thickness, called the ***reduction***:

$$r = d/h_o \qquad (2)$$

Where r = reduction. When a series of rolling operations are used, reduction is taken as the sum of the drafts divided by the original thickness.

In addition to thickness reduction, rolling usually increases work width. This is called **spreading**, and it tends to be most pronounced with low width-to-thickness ratios and low coefficients of friction. Conservation of material is preserved, so the volume of metal exiting the rolls equals the volume entering:

$$h_o w_o L_o = h_f w_f L_f \qquad (3)$$

Where w_o and w_f are the before and after work widths, mm; and L_o and L_f are the before and after work lengths, mm. Similarly, before and after volume rates of material flow must be the same, so the before and after velocities can be related:

$$h_o w_o v_o = h_f w_f v_f \qquad (4)$$

Where v_o and v_f are the entering and exiting velocities of the work.

The rolls contact the work along a contact arc defined by the angle α. Each roll has radius R, and its rotational speed gives it a surface velocity v_r. This velocity is greater than the entering speed of the work v_o and less than its exiting speed v_f. Since the metal flow is continuous, there is a gradual change in velocity of the work between the rolls.

However, there is one point along the arc where work velocity equals roll velocity. This is called the **no-slip point**, also known as the **neutral point**. On either side of this point, slipping and friction occur between roll and work. The amount of slip between the rolls and the work can be measured by means of the ***forward slip***, a term used in rolling that is defined:

$$s = v_f - v_r / v_r \qquad (5)$$

Where s = forward slip; v_f = final (exiting) work velocity, m/s; and v_r = roll speed, m/s.

The true strain experienced by the work in rolling is based on before and after stock thicknesses. In equation form,

$$\varepsilon = \ln h_o/h_f \qquad (6)$$

The true strain can be used to determine the average flow stress $\bar{Y}_f$ applied to the work material in flat rolling. Recall from the previous chapter, Eq., that

$$\bar{Y}_f = K\varepsilon^n / 1+n \qquad (7)$$

The average flow stress will be useful to compute estimates of force and power in rolling.

Friction in rolling occurs with a certain coefficient of friction, and the compression force of the rolls, multiplied by this coefficient of friction, results in a friction force between the rolls and the work. On the entrance side of the no-slip point, friction force is in one direction, and on the other side it is in the opposite direction. However, the two forces are not equal. **The friction force on the entrance side is greater, so that the net force pulls the work through the rolls.** If this were not the case, rolling would not be possible. **There is a limit to the maximum possible draft that can be accomplished in flat rolling with a given coefficient of friction, given by:**

$$d_{max} = \mu^2 R \qquad (8)$$

Where d_{max} = maximum draft, mm; μ = coefficient of friction; and R = roll radius mm. The equation indicates that if friction were zero, draft would be zero, and it would be impossible to accomplish the rolling operation.

Coefficient of friction in rolling depends on lubrication, work material, and working temperature. In cold rolling, the value is around 0.1; in warm working, a typical value is around 0.2; and in hot rolling, J.L is around 0.4. Hot rolling is often characterized by a condition called sticking, in which the hot work surface adheres to the rolls over the contact arc. This condition often occurs in the rolling of steels and high-temperature alloys. When sticking occurs, the coefficient of friction can be as high as 0.7. The consequence of sticking is that the surface layers of the work are restricted to move at the same speed as the roll speed Vr; and below the surface, deformation is more severe in order to allow passage of the piece through the roll gap.

An approximation can be calculated based on the average flow stress experienced by the work material in the roll gap. That is,

$$\boldsymbol{F = \bar{Y}_f\ w\,L} \qquad (10)$$

Where $\bar{Y}_f$ = average flow stress from Eq. (7), MPa; and the product *w L* is the roll-work contact area, mm^2. Contact length can be approximated by

$$L = \sqrt{R(h_o - h_f} \qquad (11)$$

The torque in rolling can be estimated by assuming that the roll force is centered on the work as it passes between the rolls, and that it acts with a moment arm of one half the contact length *L*. Thus, torque for each roll is

$$\boldsymbol{T = 0.5FL} \qquad (12)$$

The power required to drive each roll is the product of torque and angular velocity. Angular velocity is 2N, where N = rotational speed of the roll. Thus, the power for each roll is 2NT. Substituting Eq. (12) for torque in this expression for power, and doubling the value to account for the fact that a rolling mill consists of two powered rolls, we get the following expression:

$$\boldsymbol{P = 2\pi NFL} \qquad (13)$$

Where P = power, J/s or W; N = rotational speed, l/s (rev/min); F = rolling force, N; and L = contact length, m.

EXAMPLE

A 300-mm-wide strip 25 mm thick is fed through a rolling mill with two powered rolls each of radius = 250 mm. The work thickness is to be reduced to 22 mm in one pass at a roll speed of 50 rev/min. The work material has a flow curve defined by K = 275 MPa and n = 0.15, and the coefficient of friction between the rolls and the work is assumed to be 0.12. Determine if the friction is sufficient to permit the rolling operation to be accomplished. If so, calculate the roll force, torque, and horsepower.

Solution: The draft attempted in this rolling operation is

$d=25 - 22= 3$ mm

From Eq. (8), the maximum possible draft for the given coefficient of friction is

$d_{max} = (0.12)^2(250) = 3.6$ mm

Since the maximum allowable draft exceeds the attempted reduction, the rolling operation is feasible. To compute rolling force, we need the contact length L and the average flow stress Y_f. The contact length is given by Eq. (11):

$L = \sqrt{250 (25 - 22)} = 27.4$ mm

$\bar{Y}_f$ is determined from the true strain:

$\varepsilon = \ln 25/22 = 0.128$

$\bar{Y}_f = 275(0.128)^{0.15}/ 1.15 = 175.7$ MPa

Rolling force is determined from Eq. (10):

$F = 175.7(300)(27.4) = 1,444,786$ N

Torque required to drive each roll is given by Eq. (12):

$T = 0.5 (1,444,786) (27.4) (10^{-3}) = 19,786$ N-m

and the power is obtained from Eq. (13):

$P = 2\pi (50) (1,444,786) (27.4) (10^{-3}) = 12,432,086$ N-m/min = 207,201 N-m/s (W)

It can be seen from this example that large forces and power are required in rolling.

Inspection of Eqs. (10) and (13) indicates that force and/or power to roll a strip of a given width and work material can be reduced by any of the following: **(1) using hot rolling rather than cold rolling to reduce strength and strain hardening (K and n) of the work material; (2) reducing the draft in each pass; (3) using a smaller roll radius R to reduce force; and (4) using a lower rolling speed N to reduce power.**