Chapter Six : Metal Forming

6.1. Introduction

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 define as the deformation processes.

- 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.
- Metal forming processes can be classified into two basic categories**: bulk deformation processes and sheet metal working processes**.

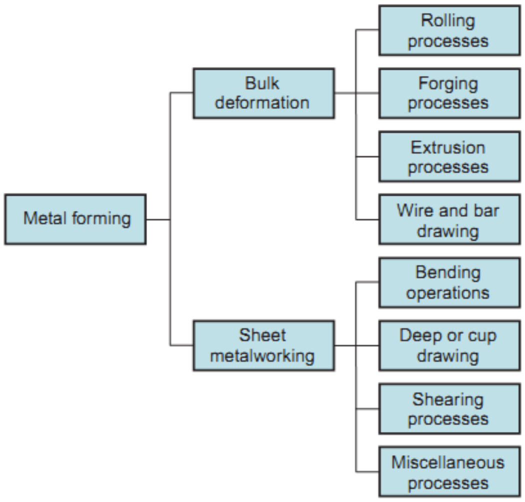


Figure 6.1 Classification of metal forming operations.

❖ 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 workparts that have this low area to volume ratio. Starting work shapes for these processes include cylindrical billets and rectangular bars. Figure 6.2 illustrates the following basic operations in bulk deformation:

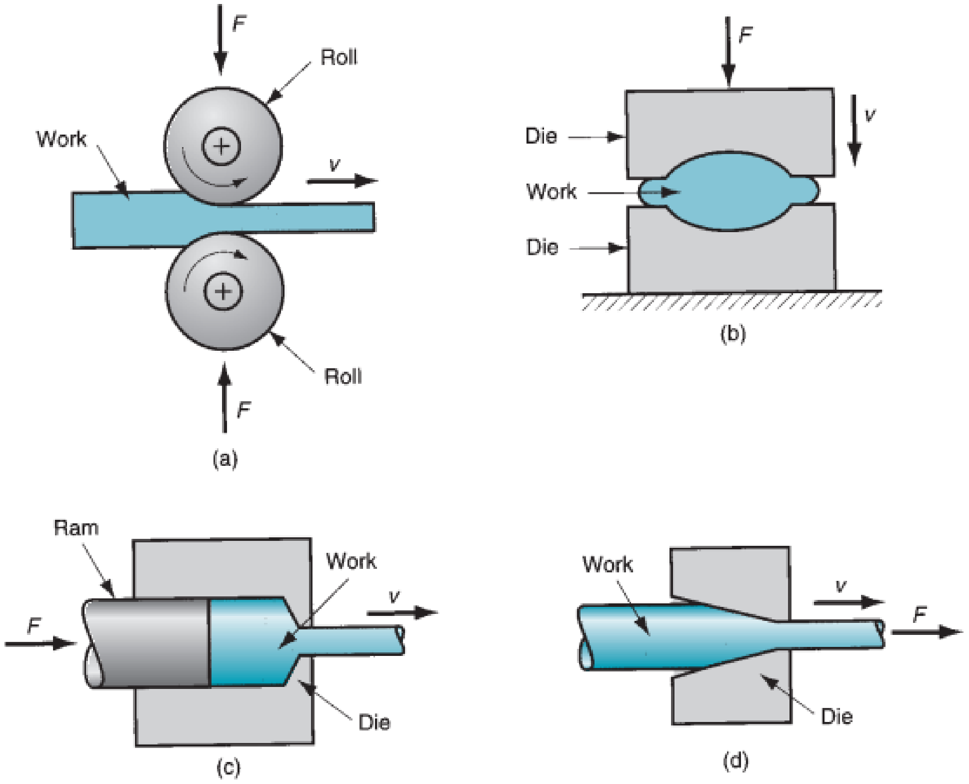


Figure 6.2 Basic bulk deformation processes: (a) rolling, (b) forging, (c) extrusion, and (d) drawing. Relative motion in the operations is indicated by v; forces are indicated by F.

- **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.

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 basic sheet metal operations are sketched in Figure 6.3 and are defined as follows:

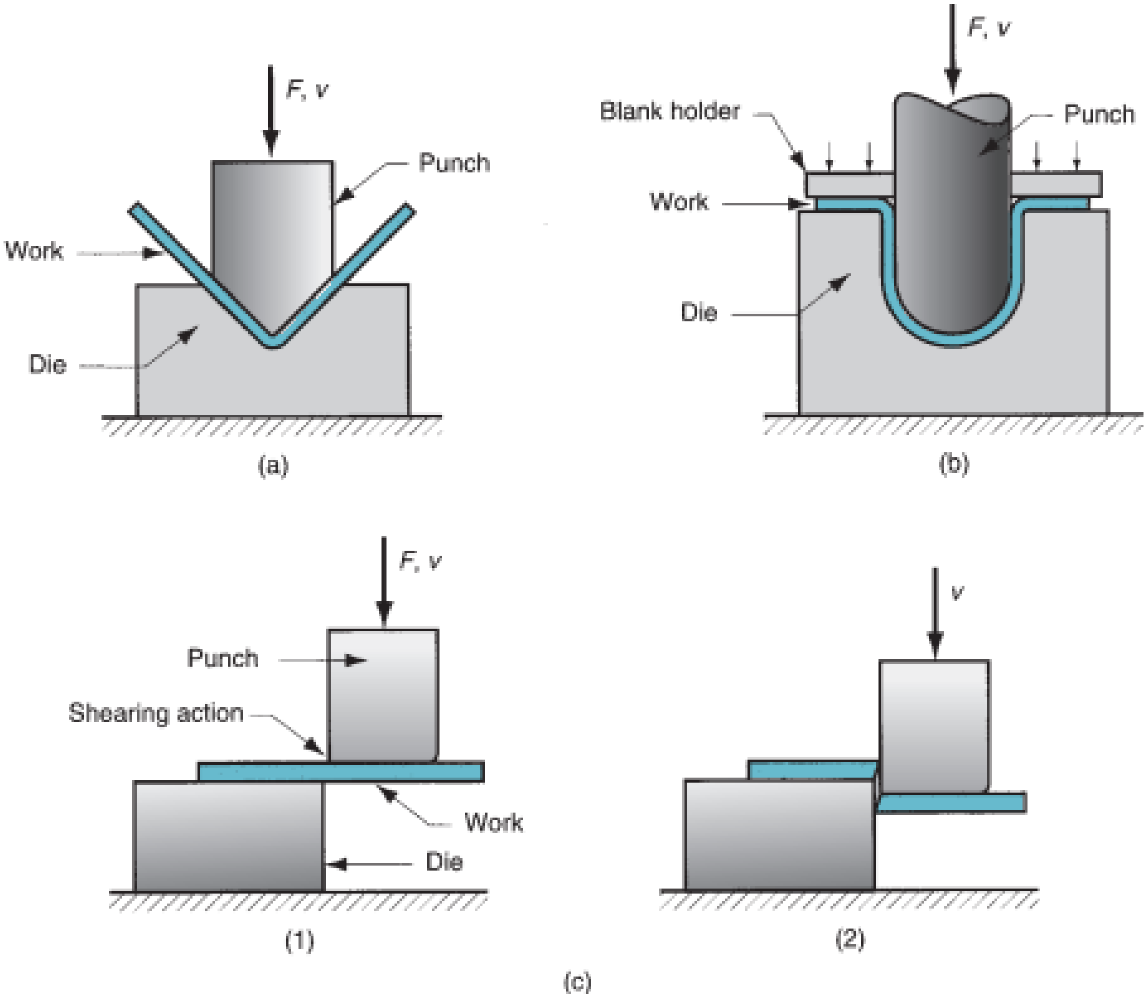


Figure 6.3 Basic sheet metalworking operations: (a) bending, (b) drawing, and (c) shearing: (1) as punch first contacts sheet, and (2) after cutting. Force and relative motion in these operations are indicated by F and v.

- **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 6.3(b). To distinguish this operation from bar and wire drawing, the terms cup drawing or deep drawing are often used.

- **Shearing**: This process seems some what 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 6.3(c) . Although it is not a forming process, it is included here because it is a necessary and very common operation in sheet metalworking.

6.2 Rolling:

Rolling is a deformation process in which the thickness of the work is reduced by compressive forces exerted by two opposing rolls. The rolls rotate as illustrated in Figure 6.4 to pull and simultaneously squeeze the work between them. The basic process shown in our figure is flat rolling, used to reduce the thickness of a rectangular cross section. A closely related process is shape rolling, in which a square cross section is formed into a shape such as an I-beam.

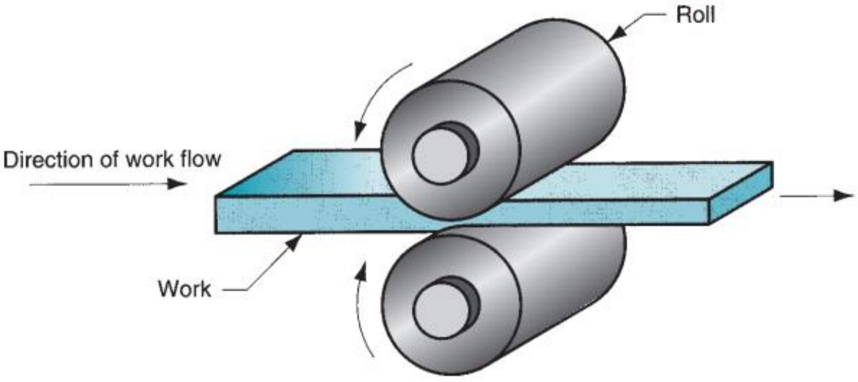


Figure 6.4 The rolling process (specifically, flat rolling).

❖ Hot Rolling

Hot rolling owing to the large amount of deformation required. Hot-rolled metal is generally free of residual stresses, and its properties are isotropic. **Disadvantages** of hot rolling are that the product cannot be held to close tolerances, and the surface has a characteristic oxide scale. The coarse structure of cast ingot is convened into a fine grained structure using rolling process as shown in Figure 6.5.

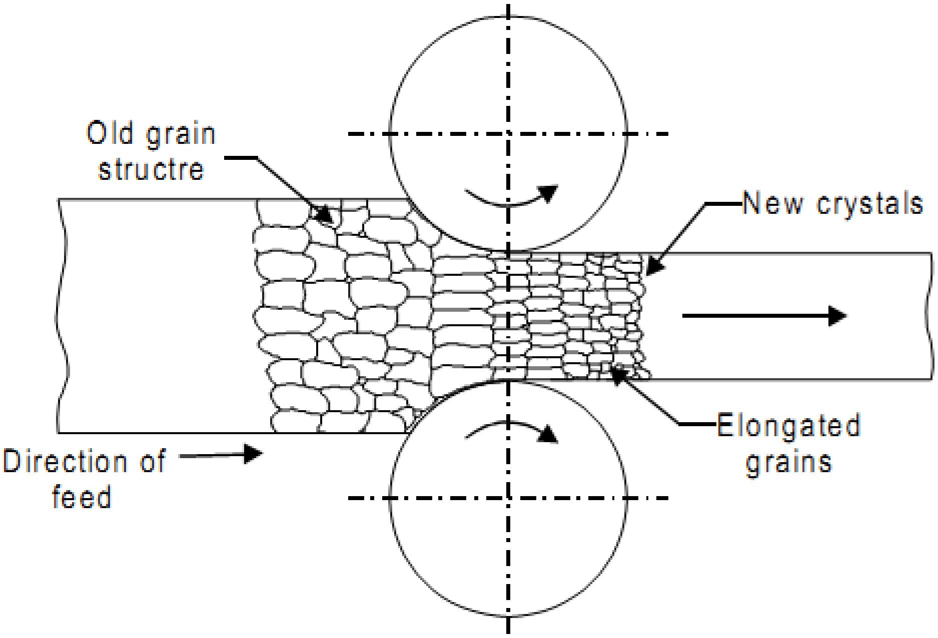


Figure 6.5 Grain refinement in hot rolling process

❖ Cold Rolling

Cold rolling strengthens the metal and permits a tighter tolerance on thickness. In addition, the surface of the cold-rolled sheet is absent of scale and generally superior to the corresponding hot-rolled product. These characteristics make cold-rolled sheets, strips, and coils ideal for stampings, exterior panels, and other parts of products ranging from automobiles to appliances and office furniture. Figure 6.6 shows some of these rolled steel products.

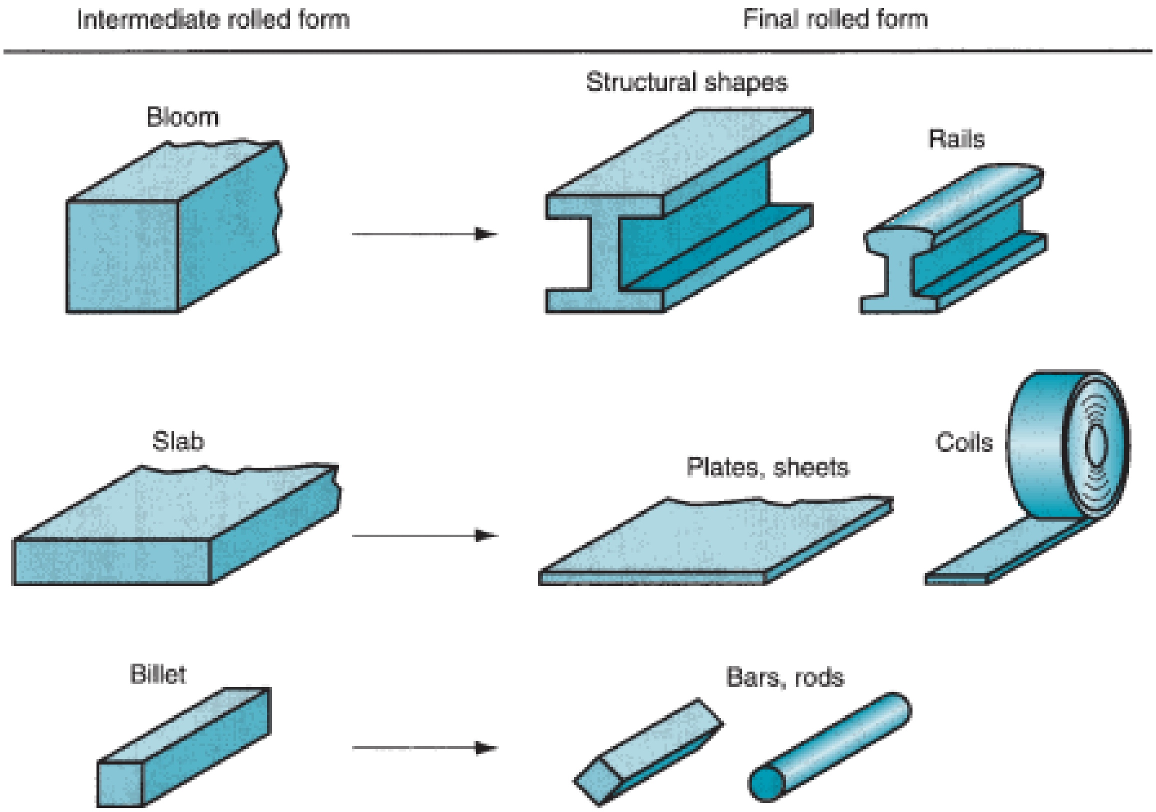
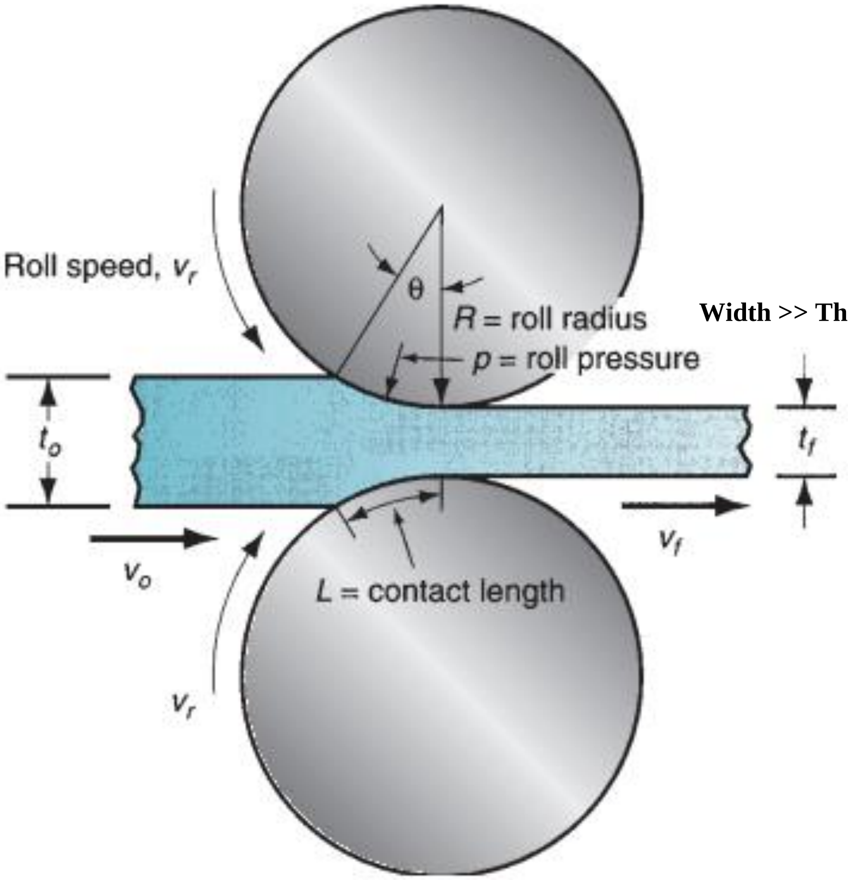


Figure 6.6 Some of the steel products made in a rolling mill.

6.2 Flat Rolling and its Analysis

Flat rolling is illustrated in Figures 6.4 and 6.7. It involves the rolling of slabs, strips, sheets, and plates workparts 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:



Width >> Thickness rectangular Cross Section

Figure 6.7 Side view of flat rolling, indicating before and after thicknesses, work velocities, angle of contact with rolls, and other features.

t_o: Original thickness (mm, in)

t_f : Final thickness (mm, in)

v_o: Entering velocity of work (m/s, ft/s)

v_f: Exiting velocity of work (m/s, ft/s)

v_r: Roll speed (m/s, ft/s)

R: Radius

P: Roll pressure

θ: Angle of contact with rolls

- **Thickness Reduction:**

$d = t_o - t_f$

d: Draft (mm, in)

$$r = \frac{d}{t_o}$$

as a friction r: Reduction in one rolling operation

when a series of rolling operations are used:

$$r = \frac{d_1 + d_2 + d_3 + \cdots + d_n}{t_o}$$

- **Volume Flow**

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 matter is preserved, so the volume of metal exiting the rolls equals the volume entering

Rolling usually increses work width (sperading).

It is pronounced with $\frac{width}{thickness}$ (low) and low coefficient of friction.

Width: Small

Thickness: Large

But:

$t_o w_o L_o = t_f w_f L_f$ (Conservation of matter is preserved)

w_o: Original work width (mm, in)

w_f: Final work width (mm, in)

L_o: Original work length (mm, in)

L_f: Final work length (mm, in)

Similarly, before and after volume rates of material flow must be the same, so the before and after velocities can be related:

$$t_o w_o v_o = t_f w_f v_f$$

$$A_o v_o = A_f v_f \qquad (Q_o = Q_f)$$

- **The Slip**

The rolls contact the work along an arc defined by the angle θ. 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:

$v_r > v_o$

$v_r < v_f$

- Since metal flow is continuous then there is a gradual change in velocity of work between rolls.
- no-slip point or netural point is one point along the arc where work velocity = roll velocity.
- on either side of no-slip-point, slipping and friction occur between roll and work.

  then:

  $s = \frac{v_f - v_r}{v_r}$ (*s*: forward slip amount of slip between roll & work)

Stress & Strain

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

$$\epsilon = ln\frac{t_o}{t_f}$$

ϵ: true strain in rolling experienced by the work.

The true strain can be used to determine the average flow stress $\bar{Y}_f$ applied to the work material in flat rolling.

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

K: Strength coefficient (MPa)

n: Strain hardening exponent

$\bar{Y}_f$: Avarage flow stress mean flow stress (MPa)

ϵ: Maximum strain value during deformation

The average flow stress is used to compute estimates of force and power in rolling.

Friction

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 therolls 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.

$F_f = F_{roll} * \mu$

μ: Friction cofficient

F_f: Friction Force between roll & work

F_{roll}: Roll force

F_{fl}: Left friction force

F_{fr}: Right friction force

$F_{fl} > F_{fr}$ Alwase so that the net force pulls the work through the rolls.

There is a limit to the maximum possible draft that can be accomplished in flat rolling with a given coefficient of friction, defined by

$$d_{max.} = \mu^2 R$$

limit of max. possible draft with a sufficient μ to permit rolling to be accomplished $d_{max.}$=***max. draft***

if $\mu = 0.0$ then d=0.0 then no rolling

- μ depends on :
  1. Lubrication
  2. Work materials
  3. Working temperature.

in cold rolling: $\mu \simeq 0.1$

in warm rolling: $\mu \simeq 0.2$

in hot rolling: $\mu \simeq 0.4$

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 v_r ; and below the surface, deformation is more severe in order to allow passage of the piece through the roll gap.

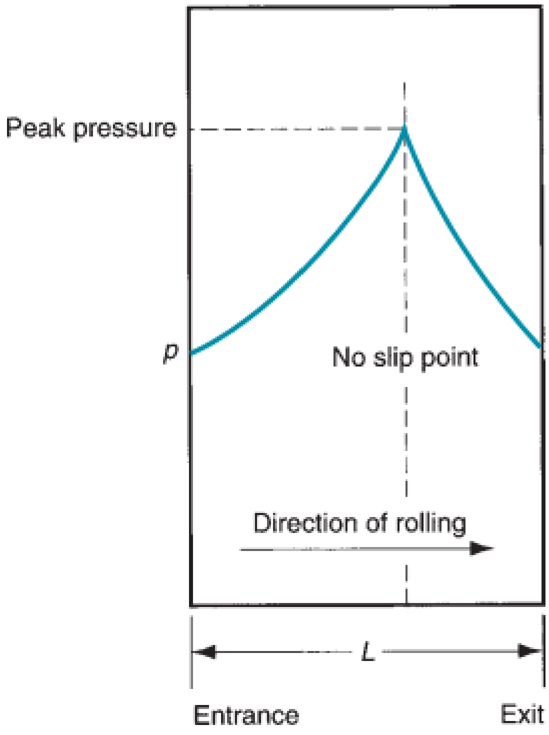
- **Roll Force (F_r)**

Given a coefficient of friction sufficient to perform rolling, roll force F required to maintain separation between the two rolls can be computed by integrating the unit roll pressure (shown as p in Figure 6.7) over the roll-work contact area. This can be expressed:

$$F_r = w \int_0^L p dL$$

L: Lenth of contact betweent rolles and work

F_r: Rolling force (N)



area beneath the curve, representing the integration in Eq. (F_r)

contact length

Figure 6.8 Typical variation in pressure along the contact length in flat rolling. The peak pressure is located at the neutral point. The area beneath the curve, representing the integration in Eq. (F_r), is the roll force F_r

An approxima tion of the results obtained by Eq. (F_r) can be calculated based on the average flow stress experienced by the work material in the roll gap. That is

$$F_r = \bar{Y}_f \, wL$$

$\bar{Y}_f$: Avarage flow stress

wL: roll-work contact area (mm^2, in^2)

Contact length can be approximated by $L = \sqrt{R(t_o - t_f)}$

Torque & Power

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

$T = 0.5\,F_r L$ for each roll

The power required to drive each roll is the product of torque and angular velocity. Angular velocity is $2\pi N$, where *N*=rotational speed of the roll. Thus, the power for each roll is $2\pi NT$. Substituting Eq. (*T*) 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:

$$P = T\,w$$

P: Power (J/s)

w: Angular velocity of roll rad/s

$w = 2\pi N/60$

N: Rotational Speed of roll (1/s, rev/min)

$$P = 0.5 F_r L \frac{2\pi N}{60}$$

$$P = \pi N F_r \frac{L}{60} \quad (w)\ \ for\ one\ roll$$

$$P = 2\pi N F_r \frac{L}{60} \quad (w)\ \ for\ two\ roll$$

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:

$d = t_o - t_f$

$d = 25 - 22 = 3\ mm$

$d_{max.} = \mu^2 R$

$d_{max.} = (0.12)^2 (0.25) = 0.0036\ m = 3.6\ mm$

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 $\bar{Y_f}$.

$\boldsymbol{F_r, T, p} = ?$

$F_r = \bar{Y}_f\, wL$

$$L = \sqrt{R(t_o - t_f)} = \sqrt{0.25(25-22)} = \sqrt{0.25 * 3 * 10^{-3}} = 27.4\ mm$$

$$\epsilon = ln\frac{t_o}{t_f} = ln\frac{25}{22} = 0.128$$

$$\bar{Y_f} = \frac{K\,\epsilon^n}{1+n} = \frac{275\,(0.128)^{0.15}}{1+0.15} = 175.7\ MPa$$

$F_r = \overline{Y}_f\, wL = 175.7*10^{3}*300*10^{-3}*27.4*10^{-3} = \mathbf{1444.254\ kN}$

$$T = 0.5\, F_r L = 0.5 * 1444.254 * \frac{27.4}{1000} = \mathbf{19.786\ kN.m}$$

$$P = 2\pi N F_r \frac{L}{60} = 2\pi * 50 * 1444.254 * \frac{27.4 * 10^{-3}}{60} = \mathbf{207.1 kW}$$

1 Horsepower = 745.7 W

$$HP = \frac{207.1 * 10^{3}}{745.7} = 278\, hp$$

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

To reduced forces and power 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 (d) in each pass.

(3) using a smaller roll radius R to reduce force F_r

(4) using a lower rolling speed N to reduce power.

6.3 Shape Rolling

- In shape rolling, the work is deformed into a contoured cross section. Products made by shape rolling include construction shapes such as I-beams, L-beams, and U-channels; rails for railroad tracks; and round and square bars and rods (see Figure 6.6).
- Most of the principles that apply in flat rolling are also applicable to shape rolling. Shaping rolls are more complicated; and the work, usually starting as a square shape, requires a gradual transformation through several rolls in order to achieve the final cross section.
- Its goal is to achieve uniform deformation throughout the cross section in each reduction. Otherwise, certain portions of the work are reduced more than others, causing greater elongation in these sections. The consequence of nonuniform reduction can be warping and cracking of the rolled product. Both horizontal and vertical rolls are utilized to achieve consistent reduction of the work material.

6.4 Rolling Mills

Various rolling mill configurations are available to deal with the variety of applications and technical problems in the rolling process. The basic rolling mill consists of two opposing rolls and is referred to as a two-high rolling mill

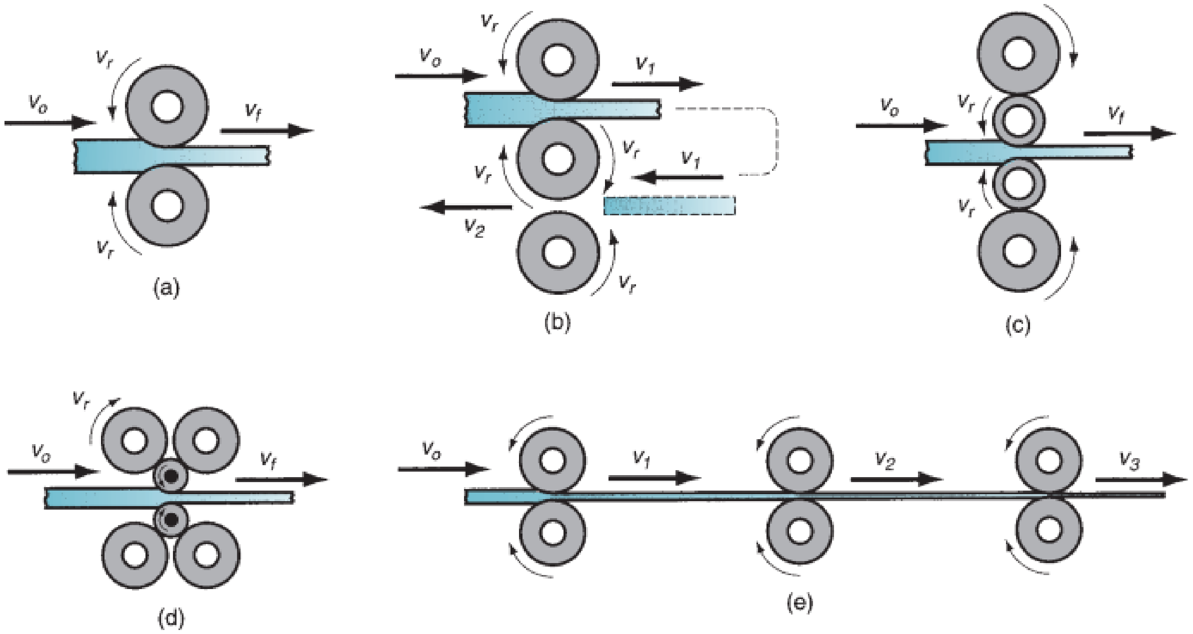


Figure 9.9 Various configurations of rolling mills:

(a) 2-high, (b) 3-high, (c) 4-high, (d) cluster mill, and (e) tandem rolling mill

➢ Two-High Rolling Mill

- The rolls in these mills have diameters in the range of 0.6 to 1.4 m (2.0–4.5 ft).
- The two-high configuration can be either reversing or nonreversing.
- In the nonreversing mill, the rolls always rotate in the same direction, and the work always passes through from the same side.

- The reversing mill allows the direction of roll rotation to be reversed, so that the work can be passed through in either direction. This permits a series of reductions to be made through the same set of rolls.
- The disadvantage of the reversing configuration is the significant angular momentum possessed by large rotating rolls and the associated technical problems involved in reversing the direction.

➢ Three-High Rolling Mill

- There are three rolls in a vertical column, and the direction of rotation of each roll remains unchanged. To achieve a series of reductions.
- The equipment in a three-high rolling mill becomes more complicated, because an elevator mechanism is needed to raise and lower the work.

➢ Four-High Rolling Mill

- The four-high rolling mill uses two smaller-diameter rolls to contact the work and two backing rolls behind them.
- Roll-work contact length is reduced with a lower roll radius, and this leads to lower forces, torque, and power.
- Owing to the high roll forces, these smaller rolls would deflect elastically between their end bearings as the work passes through unless the larger backing rolls were used to support them.

➢ Cluster Rolling Mill

- Another roll configuration that allows smaller working rolls.

➢ Tandem Rolling Mill

- It is used to achieve higher through put rates in standard products.
- a typical tandem rolling mill may have eight or ten stands, each making a reduction in thickness or a refinement in shape of the work passing through.
- With each rolling step, work velocity increases, and the problem of synchronizing the roll speeds at each stand is a significant one.