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Manufacturing Processes for Engineering Materials

SIXTH EDITION IN SI UNITS

Serope Kalpakjian • Steven R. Schmid

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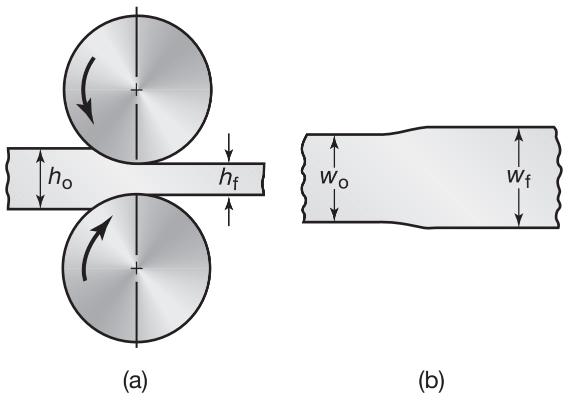

FIGURE 6.35 Increase in the width of a strip (spreading) during flat rolling. (a) Side view; (b) top view. Spreading can be similarly observed when dough is rolled on a flat surface with a rolling pin.

of the entering material; (b) decreasing friction; and (c) increasing ratios of roll-radius to strip-thickness. One technique of prevent spreading is by using a pair of vertical rolls that constrain the edges of the product being rolled, known as an **edger mill**.

6.3.2 Defects in Rolled Products

There may be surface defects on rolled plates and sheets, or structural defects within the material. **Surface defects** may result from inclusions and impurities in the material, scale, rust, dirt, roll marks, and other causes related to the prior treatment and working of the material. In hot rolling of blooms, billets, and slabs, the surface is usually preconditioned by various means, such as by **scarfing** (using a torch).

Structural defects can affect the integrity of the rolled product. Some typical defects are shown in Fig. 6.36. **Wavy edges** are caused by bending of the rolls, whereby the edges of the strip become thinner than at the center. Because the edges then elongate more than the center and are restrained by the bulk of the material from expanding freely, they buckle. The cracks shown in Fig. 6.36b and c are usually caused by low material ductility and barreling of the edges. **Alligatoring** is a complex phenomenon that results from inhomogeneous deformation of the material during rolling or from defects in the original cast ingot, such as pipe (see Section 6.4.4).

Residual stresses. Residual stresses can develop in rolled plates and sheets because of inhomogeneous plastic deformation in the roll gap. Small-diameter rolls and/or small reductions in thickness tend to deform

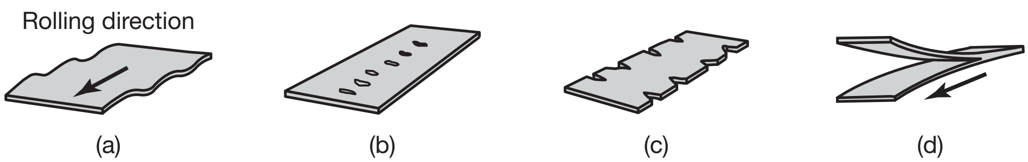

FIGURE 6.36 Schematic illustration of some defects in flat rolling: (a) wavy edges; (b) zipper cracks in the center of strip; (c) edge cracks; (d) alligatoring.

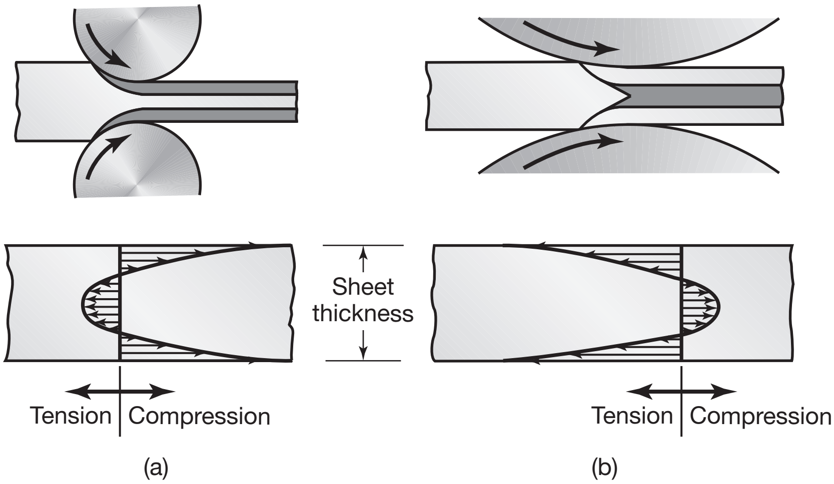

FIGURE 6.37 The effect of roll radius on the type of residual stresses developed in flat rolling: (a) small rolls and/or small reduction in thickness; and (b) large rolls and/or large reduction in thickness.

the metal plastically at its surfaces (similarly to shot peening or roller burnishing as described in Section 4.5.1). This type of deformation generates compressive residual stresses on the surfaces and tensile stresses in the bulk (Fig. 6.37a). Large-diameter rolls and/or high reductions, on the other hand, tend to deform the bulk to a greater extent than the surfaces, because of friction at the surfaces along the arc of contact. This situation generates tensile residual stresses on the surface, as shown in Fig. 6.37b. For many applications, these residual stresses can compromise performance.

6.3.3 Vibration and Chatter in Rolling

Vibration and *chatter* in rolling, as well as other metalworking operations, can have significant effects on product quality and productivity. For example, it has been estimated that modern rolling mills could operate at speeds up to 50% higher were it not for chatter. Considering the very high cost of rolling mills, this issue is a major economic concern. Chatter is generally defined as *self-excited vibration*, and can occur in such metal forming and machining processes as rolling, extrusion, drawing, machining, and grinding, as described in Sections 8.12 and 9.6.8. In rolling, it leads to small random variations in the thickness of the rolled sheet and, significantly, in its surface finish, and could lead to excessive material scrap; it has been found to occur predominantly in *tandem mills* (See Fig. 6.39d).

Vibration and chatter result from interactions between the structure of the mill stand and the dynamics of the rolling operation. Several variables are involved, but rolling speed and lubrication have been found to be the two most important parameters. The vibration modes commonly encountered in rolling are classified as torsional, third-octave, and fifth-octave chatter (octave meaning a measure of musical pitch - it is the interval between one musical pitch and another with half its frequency).

1. **Torsional chatter** is characterized by a low resonant frequency (approximately 5 to 15 Hz); it is usually a result of forced vibration (see Section 8.12), although it can also occur simultaneously with

third-octave chatter. Torsional chatter is usually not significant unless it is due to such factors as malfunctioning speed controls, broken gear teeth, and misaligned shafts.

2. **Third-octave chatter** occurs around the frequency range of the third musical octave (128 to 256 Hz) and is *self-excited*; that is, energy from the rolling mill is transformed into vibratory energy, regardless of the presence of any external forces (*forced vibration*). Third-octave chatter is most serious in tandem mills (see Section 6.3.4). This mode of vibration is the most serious in rolling, as it leads to significant gage variations, fluctuations in strip tension between the stands, and often results in strip breakage. Third-octave chatter is usually controlled by reducing the rolling speed. Although not always practical to implement, this type of chatter can be reduced by (a) increasing the distance between the stands of the tandem mill; (b) increasing the strip width, w; (c) incorporating *dampers* (see Section 8.12) in the roll supports; (d) decreasing the reduction per pass (draft); (e) increasing the roll radius R; and (f) increasing the strip-roll friction coefficient.
3. **Fifth-octave chatter** occurs in the frequency range of 550 to 650 Hz. It has been attributed to chatter marks that develop on work rolls, caused by (a) extended operation at certain critical speeds; (b) surface defects on a backup roll or in the incoming strip; and/or (c) improperly ground rolls. The chatter marks or striations are then imprinted onto the rolled sheet, thus adversely affecting its surface finish and appearance. Moreover, fifth-octave chatter is undesirable because of the objectionable noise it generates. This type of chatter can be controlled by (a) adjusting the mill speed; (b) using backup rolls of progressively larger diameters in the stands of a tandem mill; (c) avoiding chatter in grinding the rolls; and (d) eliminating the external sources of any other vibrations in the mill stand.

6.3.4 Flat-Rolling Practice

The initial breaking down of a cast ingot by hot rolling (at temperature similar to forging, Table 6.3) converts the coarse-grained, brittle, and porous structure into a *wrought* structure (Fig. 6.27) with finer grains and enhanced ductility.

The product of the first hot-rolling operation is called a **bloom** or **slab** (See Fig. 6.26). A bloom usually has a square cross section, at least 150 mm on the side; a slab is rectangular in cross section. Blooms are further processed by *shape rolling* them into structural shapes, such as I-beams and railroad rails; slabs are rolled into plates and sheet. **Billets** are usually square in cross section and their area is smaller than blooms. Billets are shape rolled into various shapes, such as round rods and bars. Hot-rolled round rods are used as the starting material for rod and wire drawing and are called **wire rods**.

In hot rolling of blooms, billets, and slabs, the surface of the material is usually *conditioned* (prepared for a particular operation) prior to rolling. Conditioning is done by such means as scarfing (flame cutting) to remove heavy scale or by rough grinding. Prior to cold rolling, the scale developed during hot rolling (or any other surface defects) may be removed by *pickling* with acids, or by mechanical means such as grinding or blasting with water).

Pack rolling is a flat-rolling operation in which two or more layers of metal are rolled together, thus improving productivity. Aluminum foil, for example, is pack rolled in two layers; it can easily be observed that one side of foil is matte and the other side is shiny. The foil-to-roll side is shiny and bright (because it has been in contact with the polished roll surfaces); the foil-to-foil side is lubricated to prevent cold welding and as a result has a matte and satiny finish due to orange peel.

Mild steel, when stretched during sheet forming operations, undergoes **yield-point elongation**, causing surface irregularities called **stretcher strains** or **Lüder's bands** (see also Section 7.2.1). To avoid this phenomenon, the sheet metal is typically subjected to a light pass of 0.5–1.5% reduction, known as **temper rolling** (*skin pass*).

A rolled sheet may not be sufficiently flat as it leaves the roll gap, because of variations in the material or in the processing parameters during rolling. To improve flatness, the strip is passed through a series of **leveling rolls**. Each roll is usually driven separately with individual electric motors; the strip is flexed in opposite directions as it passes through the sets of rollers. Several different roller arrangements are used (Fig. 6.38).

Sheet thickness is identified by a **gage number**; the smaller the number, the thicker is the sheet. There are various numbering systems for different sheet metals. Rolled sheets of copper and brass are also identified by thickness changes during rolling, such as $\frac{1}{4}$-hard, $\frac{1}{2}$-hard, and so on.

Lubrication. Ferrous alloys are usually hot rolled without a lubricant, although graphite may be used. Aqueous solutions are used to cool the rolls and break up the scale. Nonferrous alloys are hot rolled using a variety of compounded oils, emulsions, and fatty acids. Cold rolling uses low-viscosity lubricants, including mineral oils, emulsions, paraffin, and fatty oils.

Equipment. A variety of rolling equipment is available with several roll arrangements; the major types are shown in Fig. 6.39. Small-diameter rolls are preferable because roll force is lower and roll flattening is less likely. On the other hand, small rolls deflect under the roll forces; they are

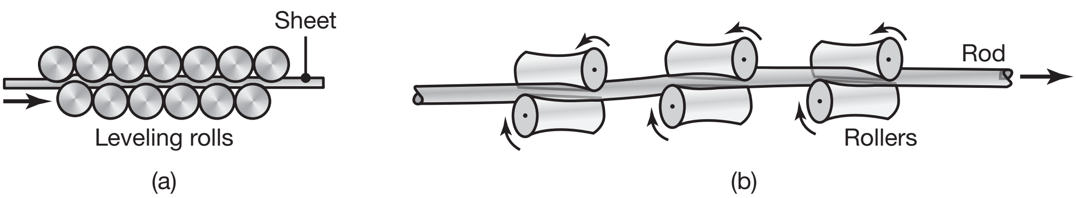

FIGURE 6.38 Schematic illustrations of roller leveling to (a) flatten rolled sheets and (b) straighten round rods.

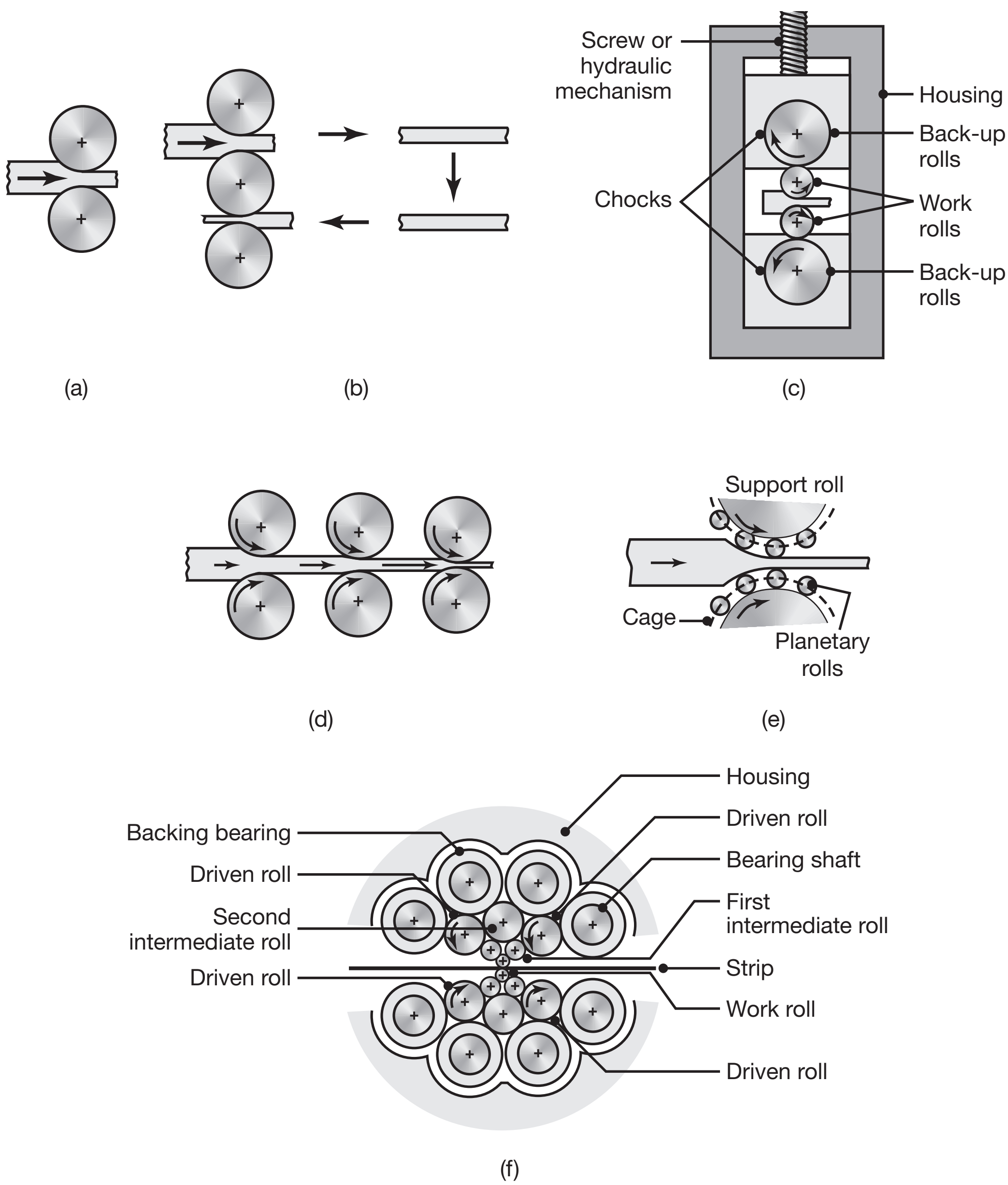

FIGURE 6.39 Schematic illustration of various roll arrangements: (a) two-high mill; (b) three-high mill; (c) four-high mill; (d) tandem rolling, with three stands; (e) planetary mill; and (f) cluster (*Sendzimir*) mill.

supported by other rolls (*backing rolls*) to maintain dimensional control (Fig. 6.39c and e).

Two-high or **three-high** rolling mills (developed in the mid-1800s) typically are used for initial breakdown passes on cast ingots (*primary roughing*), with roll diameters ranging up to 1400 mm. The **cluster mill** (**Sendzimir**, or **Z mill**; Fig. 6.39e) is particularly suitable for cold rolling thin sheets or foils. The rolled product obtained in a cluster mill can be as wide as 5000 mm and as thin as 0.0025 mm.

The diameter of the work roll (smallest roll) can be as small as 6 mm, and is usually made of tungsten carbide for rigidity, strength, and wear resistance.

In **tandem rolling** (Fig. 6.39d), the strip is rolled continuously as its passes through a number of **stands**; a group of stands is called a **train**. Control of the gage and of the speed at which the strip travels through each roll gap is critical for proper operation. Flat rolling also can be carried out with front tension only, using idling rolls (**Steckel rolling**).

Stiffness in rolling mills is important for controlling dimensions. The basic requirements for roll materials are mainly strength, stiffness, and resistance to wear. Three common roll materials are cast iron, cast steel, and forged steel. For hot rolling, roll surfaces are generally roughened, and may even have notches or grooves in order to pull the metal through the roll gap at high reductions. Rolls for cold rolling are ground to a fine finish and are polished for special applications, such as aluminum foil.

Minimills. In *minimills*, scrap metal is melted in electric-arc furnaces, cast continuously, and rolled directly into specific lines of products. Each minimill produces essentially one kind of rolled product (such as rod, bar, and structural shapes) from one type of metal, and is often dedicated to markets within the mill's particular geographic area.

Integrated mills. *Integrated mills* are large facilities that involve complete operations, from the production of hot metal in a blast furnace to casting and rolling of finished products that are ready to be shipped to the customer. Nearly all integrated mills specialize in flat-rolled metal or plate. Technically, the only difference between integrated mills and minimills is the type of furnace used; however, the use of blast furnaces implies different economies of scale than electric-arc furnaces that require much larger and more elaborate facilities.

6.3.5 Miscellaneous Rolling Operations

1. **Shape rolling**. Straight structural shapes of various cross sections (such as channels I-beams and railroad rails) are rolled by passing a bloom (See Fig. 6.26) through a series of specially designed rollers (Fig. 6.40). The design of the rolls (**roll-pass design**) requires special care in order to avoid defect formation and to hold dimensional tolerances. For example, in shape rolling a channel, the reduction is different in various locations within the section; thus, elongation is not uniform throughout the cross section, which can cause warping or cracking.
2. **Ring rolling**. In this process, a small-diameter, thick ring is expanded into a larger-diameter, thinner ring, by placing the ring between two rolls, one of which is driven (Fig. 6.41). The ring thickness is reduced by moving the rolls closer as they continue rotating. Because of volume constancy, the reduction in thickness causes an increase in the ring diameter. A variety of cross sections can be ring rolled with variously shaped rolls.

QR Code 6.7 Ring-rolling operations. *Source:* Courtesy of the Forging Industry Association, www.forging.org.