Metal-Rolling Processes and Equipment

Ch 13
Forming and Shaping Processes and equipment

Forming" generally indicates changing the shape of an existing solid body.

Shaping processes typically involve the molding and casting of soft or molten materials, and the finished product is usually at or near the final desired shape.

The initial material used in forming and shaping metals is usually molten metal, which is cast into individual ingots or continuously cast into slabs, rods, or pipes.

Cast structures are converted to wrought structures by plastic-deformation processes.
Formed and shaped parts in a typical automobile
<table>
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<th>Process</th>
<th>Characteristics</th>
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| Rolling                      | **Flat**  
Production of flat plate, sheet, and foil at high speeds; good surface finish, especially in cold rolling; very high capital investment; low-to-moderate labor cost  
**Shape**  
Production of various structural shapes (such as I-beams and rails) at high speeds; includes thread rolling; requires shaped rolls and expensive equipment; low-to-moderate labor cost; requires moderate operator skill |
| Forging                      | Production of discrete parts with a set of dies; some finishing operations usually required; usually performed at elevated temperatures, but also cold for smaller parts; die and equipment costs are high; moderate-to-high labor cost; requires moderate-to-high operator skill |
| Extrusion                    | Production of long lengths of solid or hollow shapes with constant cross section; product is then cut into desired lengths; usually performed at elevated temperatures; cold extrusion has similarities to forging and is used to make discrete products; moderate-to-high die and equipment cost; low-to-moderate labor cost; requires low-to-moderate operator skill |
| Drawing                      | Production of long rod and wire with various cross sections; good surface finish; low-to-moderate die, equipment, and labor costs; requires low-to-moderate operator skill |
| Sheet-metal forming          | Production of a wide variety of shapes with thin walls and simple or complex geometries; generally low-to-moderate die, equipment, and labor costs; requires low-to-moderate operator skill |
| Powder metallurgy            | Production of simple or complex shapes by compacting and sintering metal powders; moderate die and equipment cost; low labor cost and skill |
| Processing of plastics and composite materials | Production of a wide variety of continuous or discrete products by extrusion, molding, casting, and fabricating processes; moderate die and equipment costs; requires high operator skill in processing of composite materials |
| Forming and shaping of ceramics | Production of discrete products by various shaping, drying, and firing processes; low-to-moderate die and equipment cost; requires moderate-to-high operator skill |
Metal-Rolling Processes and Equipment

Rolling is the process of reducing the thickness or changing the cross section of a long work piece by compressive forces applied through a set of rolls.

Rolling, which accounts for about 90% of all metals produced by metalworking processes.

Modern steelmaking practices and the production of various ferrous and nonferrous metals and alloys now generally involve combining continuous casting with rolling processes.

Typical products made by various rolling processes: Plates for ships, bridges, structures, machines; sheet metal for car bodies, aircraft fuselages, appliances, containers; foil for packaging; I-beams, railroad rails, architectural shapes, large rings, seamless pipe and tubing; bolts, screws, and threaded components.
Schematic outline of various flat-rolling and shape-rolling processes

Rolling first is carried out at elevated temperatures (hot rolling). During this phase, the coarse-grained, brittle, and porous structure of the ingot (or the continuously cast metal) is broken down into a wrought structure having a finer grain size and enhanced properties, such as increased strength and hardness.

Rolling typically is carried out at room temperature (cold rolling), whereby the rolled product has higher strength and hardness and a better surface finish.
Metal-Rolling Processes

Plates generally have a thickness of more than 6 mm and are used for structural applications, such as ship hulls, boilers, bridges, machinery, and nuclear vessels.

Plates can be as thick as 300 mm for large structural supports, 150 mm for reactor vessels, and 100 to 125 mm for machinery frames and warships.

Sheets generally are less than 6 mm thick and typically are provided to manufacturing facilities as coils-weighing as much as 30,000 kg-or as flat sheets for further processing into various products. Sheets typically are used for automobile and aircraft bodies, appliances, food and beverage containers, and kitchen and office equipment.

Commercial aircraft fuselages and trailer bodies usually are made of a minimum of 1-mm thick aluminum-alloy sheets. For example, the skin thickness of a Boeing 747 fuselage is 1.8 mm and of a Lockheed L1011 is 1.9 mm. Steel sheets used for automobile and appliance bodies are typically about 0.7 mm thick. Aluminum beverage cans are made from sheets 0.28 mm thick. After processing into a can, this sheet metal becomes a cylindrical body with a wall thickness of 0.1 mm. Aluminum foil (typically used for wrapping candy and chewing gum) has a thickness of 0.008 mm.
The Flat-rolling Process

A metal strip of thickness $h_o$ enters the roll gap and is reduced to thickness $h_f$ by a pair of rotating rolls, each powered individually by electric motors.

The rolls pull the material into the roll gap through a net frictional force on the material. Thus, the net frictional force must be to the right.
The Flat-rolling Process

Although friction is necessary for rolling materials just as it is in driving a car on a road, energy is dissipated in overcoming friction. Thus, increasing friction also increases rolling forces and power requirements.

Furthermore, high friction could damage the surface of the rolled product (or cause sticking, as can occur in rolling dough). Thus, a compromise is made in practice: Low and controlled friction is induced in rolling through the use of effective lubricants.

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The maximum possible draft is defined as the difference between the initial and final strip thicknesses,

\[ h_o - h_f = \mu^2 R. \]

roll radius, \( R \), and the coefficient of friction, \( \mu \).
Roll Force, Torque, and Power Requirements

The rolls apply pressure on the flat strip in order to reduce its thickness, resulting in a *roll force*, \( F \),

Note that this force appears in the figure as perpendicular to the plane of the strip, rather than at an angle. This is because, in practice, the arc of contact is very small compared with the roll radius, so we can assume that the roll force is perpendicular to the strip without causing significant error in calculations.

The *roll force* in flat rolling can be estimated from the formula

\[
F = L w Y_{\text{avg}}, \quad L = \sqrt{R \Delta h}
\]

where \( L \) is the roll-strip contact length, \( w \) is the width of the strip, and \( Y_{\text{avg}} \) is the average true stress (see Section 2.2) of the strip in the roll gap. Equation (13.2) is for a *frictionless* situation; however, an estimate of the *actual roll force*, including friction, may be made by increasing this calculated force by about 20%. 
The Flat-rolling Process

The torque on the roll is the product of $F$ and $a$. The power required per roll can be estimated by assuming that $F$ acts in the middle of the arc of contact; thus,

$$a = \frac{L}{2}.$$ Therefore, the total power (for two rolls), in S.I. units, is

$$\text{Power (in kW)} = \frac{2\pi FLN}{60,000}$$

where $F$ is in Newton's, $L$ is in meters, and $N$ is the revolutions per minute of the roll.
Reducing Roll Force

Roll forces can cause significant deflection and flattening of the rolls (as it does in a rubber tire).

Such changes in turn will affect the rolling operation. Also, the columns of the roll stand (including the housing, chocks, and bearings, may deflect under high roll forces to such an extent that the roll gap can open up significantly.

Consequently, the rolls have to be set closer than originally calculated in order to compensate for this deflection and to obtain the desired final thickness.

Schematic illustration of various roll arrangements: (a) four-high rolling mill showing various features. The stiffness of the housing, the rolls, and the roll bearings are all important in controlling and maintaining the thickness of the rolled strip; (b) two-high mill; (c) three-high mill; and (d) cluster (or Sendzimir) mill.
Roll forces can be reduced by the following means:

- Reducing friction at the roll-workpiece interface
- Using smaller diameter rolls to reduce the contact area
- Taking smaller reductions per pass to reduce the contact area
- Rolling at elevated temperatures to lower the strength of the material
- Applying front and/or back tensions to the strip
Geometric Considerations

Because of the forces acting on them, rolls undergo changes in shape during rolling. Just as a straight beam deflects under transverse load, roll forces tend to bend the rolls elastically during rolling.

For rolling sheet metals, the radius of the maximum **camber** point is generally 0.25 mm greater than that at the edges of the roll.

(a) Bending of straight cylindrical rolls caused by roll forces. (b) Bending of rolls ground with **camber**, producing a strip with uniform thickness through the strip width. Deflections have been exaggerated for clarity.
Spreading

In rolling plates and sheets with **high width-to-thickness ratios**, the width of the strip remains effectively **constant** during rolling. **However**, with smaller ratios (such as a strip with a square cross section), its width increases significantly as it passes through the rolls (an effect commonly observed in the rolling of dough with a rolling pin).

This increase in width is called **spreading**. **Spreading increases** with:

(a) decreasing width-to-thickness ratio of the entering strip (because of reduction in the width constraint),

(b) increasing friction, and

(c) decreasing ratio of the roll radius to the strip thickness.

Spreading can be prevented also by using **additional rolls** (with vertical axes) in contact with the edges of the rolled product in the roll gap (**edger mills**), thus providing a physical constraint to spreading.

Spreading in flat rolling. Note that similar spreading can be observed when dough is rolled with a rolling pin.
Vibration and Chatter

Vibration and chatter can have significant effects on product quality and the productivity of metalworking operations. Chatter, generally defined as self-excited vibration, can occur in rolling as well as in extrusion, drawing, machining, and grinding operations.

In rolling, it leads to periodic variations in the thickness of the rolled sheet and in its surface finish and, consequently, can lead to excessive scrap.

Modern rolling mills could operate at up to 50% higher speeds were it not for chatter.

Rolling speed and lubrication are found to be the two most important parameters. Although not always practical to implement, it also has been suggested that chatter can be reduced by increasing the distance between the stands of the rolling mill, increasing the strip width, decreasing the reduction per pass (draft), increasing the roll radius, increasing the strip-roll friction, and incorporating dampers in the roll supports.
Flat Rolling Practice

The initial rolling steps (breaking down) of the material typically is done by hot rolling (above the recrystallization temperature of the metal). A cast structure typically is dendritic, and it includes coarse and nonuniform grains; this structure usually is brittle and may be porous.

Changes in the grain structure of cast or of large-grain wrought metals during hot rolling. Hot rolling is an effective way to reduce grain size in metals for improved strength and ductility. Cast structures of ingots or continuous castings are converted to a wrought structure by hot working.
Flat Rolling Practice

Hot rolling converts the cast structure to a wrought structure with finer grains and enhanced ductility, both of which result from the breaking up of brittle grain boundaries and the closing up of internal defects (especially porosity).

Typical temperature ranges for hot rolling are about 450°C for aluminum alloys, up to 1250°C for alloy steels, and up to 1650°C for refractory alloys.

The product of the first hot-rolling operation is called a bloom, a slab, or a billet. A bloom usually has a square cross section, at least 150 mm on the side; a slab usually is rectangular in cross section.

Blooms are processed further by shape rolling into structural shapes such as I-beams and railroad rails.

In the hot rolling of blooms, billets, and slabs, the surface of the material usually is conditioned (prepared for a subsequent operation) prior to rolling them. Conditioning is often done by means of a torch (scarfing) to remove heavy scale or by rough grinding to smoothen surfaces. Prior to cold rolling, the scale developed during hot rolling may be removed by pickling with acids (acid etching), by such mechanical means as blasting with water, or by grinding to remove other defects as well.
A rolled sheet may not be sufficiently flat as it leaves the roll gap, due to factors such as variations in the incoming material or in the processing parameters during rolling. To improve flatness, the rolled strip typically goes through a series of leveling rolls.

(a) A method of roller leveling to flatten rolled sheets. (b) Roller leveling to straighten drawn bars.
Defects in Rolled Plates and Sheets

Defects may be present on the surfaces of rolled plates and sheets, or there may be internal structural defects. Defects are undesirable not only because they compromise surface appearance.

Several defects (such as scale, rust, scratches, gouges, pits, and cracks) have been identified in sheet metals. These defects may be caused by inclusions and impurities in the original cast material or by various other conditions related to material preparation and to the rolling operation.

Schematic illustration of typical defects in flat rolling: (a) wavy edges; (b) zipper cracks in the center of the strip; (c) edge cracks; and (d) alligating.
**Residual Stresses**

Because of nonuniform deformation of the material in the roll gap, residual stresses can develop in rolled plates and sheets, especially during cold rolling. Small-diameter rolls or small thickness reductions per pass tend to plastically deform the metal more at its surfaces than in the bulk.

(a) Residual stresses developed in rolling with small-diameter rolls or at small reductions in thickness per pass. (b) Residual stresses developed in rolling with large-diameter rolls or at high reductions per pass. Note the reversal of the residual stress patterns.
Dimensional Tolerances

Thickness tolerances for cold-rolled sheets usually range from ±0.1 to 0.35 mm, depending on the thickness. Tolerances are much greater for hot-rolled plates, because of thermal effects. Flatness tolerances are usually within mm/m for cold rolling and ±55 mm/m for hot rolling.

Surface roughness

Note that cold rolling can produce a very fine surface finish; hence, products made of cold-rolled sheets may not require additional finishing operations.

Gage number

The thickness of a sheet usually is identified by a gage number: the smaller the number, the thicker the sheet. Several numbering systems are used in industry, depending on the type of sheet metal being classified. Rolled sheets of copper and of brass also are identified by thickness changes during rolling, such as ¼ hard, ½ hard, and so on.
Rolling Mills

Several types of rolling mills and equipment are available with diverse roll arrangements. Although the equipment for hot and cold rolling is essentially the same, there are important differences in the roll materials, process parameters, lubricants, and cooling systems.

The design, construction, and operation of rolling mills require major investments. Highly automated mills produce close-tolerance, high quality plates and sheets at high production rates and low cost per unit weight, particularly when integrated with continuous casting.
In tandem rolling, the strip is rolled continuously through a number of stands to thinner gages with each pass. Each stand consists of a set of rolls with its own housing and controls; a group of stands is called a train. The control of the strip thickness and the speed at which the strip travels through each roll gap is critical.

Extensive electronic and computer controls are used in these operations, particularly in precision rolling.

An example of a tandem-rolling operation
Rolling Mills

Roll materials

The basic requirements for roll materials are strength and resistance to wear. Common roll materials are cast iron, cast steel, and forged steel; tungsten carbide is also used for small-diameter rolls, such as the working roll in cluster mill. Forged-steel rolls, although more costly than cast rolls, have higher strength, stiffness, and toughness than cast-iron rolls. Rolls for cold rolling are ground to a fine finish.

Rolls made for cold rolling should not be used for hot rolling, because they may crack from thermal cycling (heat checking) and spalling (cracking or flaking of surface layers).

Lubricants

Hot rolling of ferrous alloys is carried out without lubricants, although graphite may be used. Water-based solutions are used to cool the rolls and to break up the scale on the rolled material. Nonferrous alloys are hot rolled with a variety of compounded oils, emulsions, and fatty acids. Cold rolling is carried out with water-soluble oils or low-viscosity lubricants, such as mineral oils, emulsions, paraffin, and fatty oils.
Various Rolling Processes and Mills

Several rolling processes and mills have been developed to produce a specific family of product shapes.

Shape Rolling

Straight and long structural shapes (such as channels, I-beams, railroad rails, and solid bars) are formed at elevated temperatures by shape rolling (profile rolling), in which the stock goes through a set of specially designed rolls.

Steps in the shape rolling of an I-beam part. Various other structural sections, such as channels and rails, also are rolled by this kind of process.
Roll Forging

In this operation (also called cross rolling), the cross section of a round bar is shaped by passing it through a pair of rolls with profiled grooves. Roll forging typically is used to produce tapered shafts and leaf springs, table knives, and hand tools.

Two examples of the roll-forging operation, also known as cross-rolling. Tapered leaf springs and knives can be made by this process.
Skew Rolling

A process similar to roll forging is *skew rolling*, typically used for making ball bearings.

Round wire or rod is fed into the roll gap, and roughly spherical blanks are formed continuously by the action of the rotating rolls.

(a) Production of steel balls by the skew-rolling process. (b) Production of steel balls by upsetting a cylindrical blank. Note the formation of flash. The balls made by these processes subsequently are ground and polished for use in ball bearings.
Ring Rolling

In ring rolling, a thick ring is expanded into a large-diameter thinner one. The ring is placed between two rolls, one of which is driven while the other is idle. Its thickness is reduced by bringing the rolls closer together as they rotate. Since the volume of the ring material remains constant during plastic deformation (volume constancy), the reduction in ring thickness results in an increase in its diameter.

(a) Schematic illustration of a ring-rolling operation. Thickness reduction results in an increase in the part diameter. (b) through (d) Examples of cross sections that can be formed by ring rolling.
Ring Rolling

Typical applications of ring rolling are large rings for rockets and turbines, jet engine cases, gearwheel rims, ball-bearing and roller-bearing races, flanges, and reinforcing rings for pipes.

The process can be carried out at room temperature or at an elevated temperature, depending on the size (which can be up to 3 m, in diameter), strength, and ductility of the work piece material.
Thread rolling

Thread rolling is a cold-forming process by which straight or tapered threads are formed on round rods or wire.

The threads are formed on the rod or wire with each stroke of a pair of flat reciprocating dies.

Lubrication is important in thread-rolling operations in order to obtain a good surface finish and surface integrity and to minimize defects.

Thread-rolling processes: (a) and (b) reciprocating flat dies; (c) two-roller dies; (d) A collection of thread-rolled parts made economically at high production rates.
Thread rolling

Thread rolling is superior to other methods of thread manufacture, because machining the threads cuts through the grain-flow lines of the material, whereas rolling the threads results in a grain-flow pattern that improves the strength of the thread.

(a) Features of a machined or rolled thread. Grain flow in (b) machined and (c) rolled threads. Unlike machining, which cuts through the grains of the metal, the rolling of threads imparts improved strength because of cold working and favorable grain flow.
Rotary Tube Piercing

Also known as the Mannesmann process, this is a hot working operation for making long, thick-walled seamless pipe and tubing. This process is based on the principle that when a round bar is subjected to radial compressive forces, tensile stresses develop at the center of the bar.

An internal mandrel assists the operation by expanding the hole and sizing the inside diameter of the tube. The mandrel may be held in place by a long rod, or it may be a floating mandrel without a support.

Cavity formation in a solid, round bar and its utilization in the rotary tube piercing process for making seamless pipe and tubing.
**Tube Rolling**

The diameter and thickness of pipes and tubing can be reduced by tube which utilizes shaped rolls. Some of these operations can be carried out either with or without an internal mandrel. In the pilger mill, the tube and an internal mandrel undergo a reciprocating motion.

Schematic illustration of various tube-rolling processes: (a) with a fixed mandrel; (b) with a floating mandrel; (c) without a mandrel; and (d) pilger rolling over a mandrel and a pair of shaped rolls. Tube diameters and thicknesses also can be changed by other processes, such as drawing, extrusion, and spinning.
Various Mills

Integrated Mill. These mills are large facilities that involve complete integration of the activities—from the production of hot metal in a blast furnace to the casting and rolling of finished products ready to be shipped to the customer.

Minimills,

Each minimill produces essentially one type of rolled product (rod, bar, or structural sections such as angle iron) from basically one type of metal or alloy. The scrap metal, which is obtained locally (to reduce transportation costs), is typically old machinery, cars, and farm equipment.

Minimills have the economic advantages of low-investment optimal operations for each type of metal and product line and of low labor and energy costs.