CHAPTER 1

Introduction to Rolling Process

1.1 Definition of Rolling Process

Rolling is the most important metal forming process. More than 95% of ferrous and non-ferrous metals and alloys are processed to their usable shapes by rolling. Usable shapes of rolled metals are plate, sheet, strip, foil, different sections like rail, beam, channel, angle, bar, rod, and seamless pipe, etc., as shown in Fig. 1.1 and Fig. 1.2.

In the rolling process, permanent deformation is achieved by subjecting the material to high compressive stress by allowing the material to pass through the gap between two rotating cylindrical rolls.

The rolls may be flat or grooved, and are kept at a fixed distance apart from each other. The rolls are rotated in opposite direction by means of electrical drive system (motor, gearbox, spindle and couplings).

Depending on the direction of rotation of the rolls, the input material enters the gap between the rolls from one end and comes out from the other end with a reduced cross-section, the roll gap area being kept less than the cross-sectional area of the input material (rolling stock). For obtaining the desired final shape of rolled material, it is generally necessary to pass the material through the rotating rolls several times. During each of the passes, the roll gap is adjusted by bringing the two rolls closer to each other, or by allowing the material to pass through different set of roll gaps with diminishing cross sectional area.

The entire assembly of the rolls mounted on bearings is held in bearing blocks (called chocks), which in turn are held between the gaps of two cast frames (called housings), complete with roll gap adjustment facilities and roll driving arrangement. The entire set up is called a *rolling mill stand.* One or more number of rolling stands in combination with other necessary and related equipment to obtain finished rolled products from one or similar group of input materials is called a *rolling mill* or *rolling plant.*

Rolling process can be classified based on various conditions/methods employed in rolling. These are:

(i) Temperature of the material- thus we can have *hot rolling* (temperature above the recrystallization temperature), *warm rolling* and *cold rolling.*

(ii) Shape of the rolled product- *flat, sections* or *hollow sections rolling.*
(iii) Direction of rolling- *lengthwise*, *transverse*, and *skew rolling*.
(iv) Mode of rolling mill operation- *continuous* (unidirectional), and *reverse rolling*, where direction of rotation of rolls are reversed.

When two rolls of equal diameter and with axis lying in same plane rotate in opposite direction with same rotational speed, and the material being rolled is homogeneous in its mechanical properties and is acted upon only by the forces from the rolls, the process is called *simple rolling*.

1.2 Hot and Cold Rolling Processes

From metallurgical point of view, rolling process can be classified under two broad categories, namely (i) hot rolling and (ii) cold rolling.

1.2.1 Hot rolling

In hot rolling the material is rolled at a temperature higher than its recrystallization temperature. The advantage of hot rolling is twofold. First, at elevated temperature the strength of any metal or alloy is reduced. Thus the compressive force required for deformation is comparatively less and therefore smaller capacity rolling stand can be used for rolling operation . The second advantage of rolling a material at a temperature higher than its recrystallization temperature is that a large amount of plastic deformation can be imparted without getting it *strain hardened* . With strain hardening, the deformation stress increases as more and more deformation takes place rendering the material hard and brittle. As a result, the material becomes more and more difficult to be deformed, and beyond limit, deformation leads to various faults or defects.

The ferrous raw material for rolling various shapes is the *ingot* which is cast out of molten metal. In case of low carbon steels the ingot is quite large. It is first rolled into *blooms*. The blooms are rolled into smaller sizes, called *billets*. Large structural sections such as rails, beams, girders, channels, angle sections, and plates are rolled out of blooms, while billets are rolled into smaller structural sections, bars, plates, and strips. Alloy steel and stainless steel, produced in mini steel plants, are generally cast into smaller sizes of ingots. Non-ferrous metals like aluminum are cast into wide slabs, from which plates, sheets, and strips are obtained.

The above practice still goes on in older plants. However, the present trend is to install continuous casting units to cast smaller sections directly from liquid metal and thus eliminate bloom rolling. In some continuous casting plants, billets of small cross sections may also be continuously cast, thus eliminating even the billet rolling mill. Installation of continuous casting results in substantial saving in capital cost of the rolling plant as well as rolling process cost. Non-ferrous alloys of aluminum, brass, nickel-silver, etc., are continuously cast in bar or strip form.

Rolling of ingots to blooms and blooms to billets, and further rolling of blooms and billets to different usable products like structural sections, bars, plates, and strips are all rolled through hot rolling. Some of the products produced through hot rolling process are illustrated in Fig. 1.1.

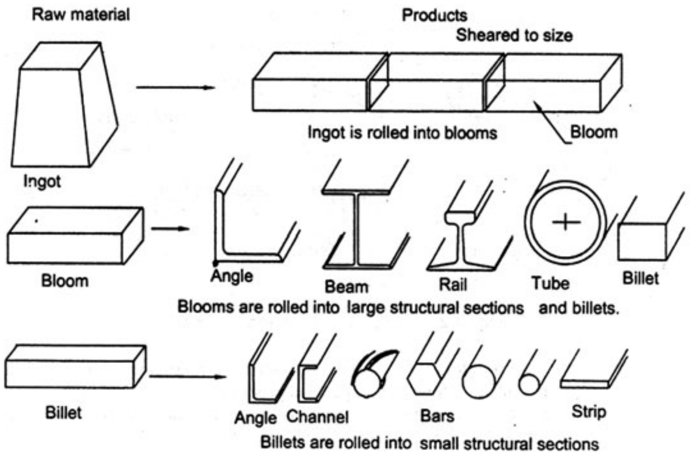


Fig. 1.1 Products produced by hot rolling

1.2.2 Cold rolling

When rolling of a material is done at room temperature or below the recrystallization temperature of the material, it is called cold rolling. Obviously, the advantages of hot rolling is absent in cold rolling. The resistance to deformation is more. Furthermore, during rolling, strain hardening takes place, i.e., the strength of the material progressively increases with increase in degree of deformation in the original material.

However, there are a few advantages also. The first one is about controlling the *grain size* and thereby achieving the desired mechanical properties of the finished rolled material. When the input material is cold rolled, the grains of the input material get elongated along the direction of rolling. Thus the effective grain size is reduced, as the surface area of each grain increases whereas their volume remains the same. With subsequent passes of rolling, the elongated grains break and the grain size becomes progressively smaller and the material gets harder and harder. After a certain percentage of volumetric deformation, the cold rolled material becomes too hard and brittle to be rolled further profitability. At this stage, the cold rolled material is *annealed*, which is nothing but heating the material in a neutral atmosphere (heating in presence of oxygen is avoided to prevent oxidation) above its recrystallization temperature. By adjusting the time for which the rolled material is kept at this higher temperature (soaking time), the size of the newly formed grains of the annealed material can be closely controlled.

Cold rolling is generally done to produce flat rolled products like sheet, plate, strip, and foil. When the length of the rolled product is too large, the material is wound and used in the coil form.

In cold rolling, since the degree of deformation, i.e., reduction in thickness of the flat product in any rolling pass, is kept low to avoid high roll separating force, several rolling passes are generally required along with requisite number of intermediate annealing. A number of rolling passes with grain deformation in the same direction gives a directional bias to the various mechanical properties of cold rolled products. Such directional bias (anisotropy) often remains even after annealing after final pass of rolling. This directionality of properties has to be taken care of during subsequent processing of cold-rolled material.

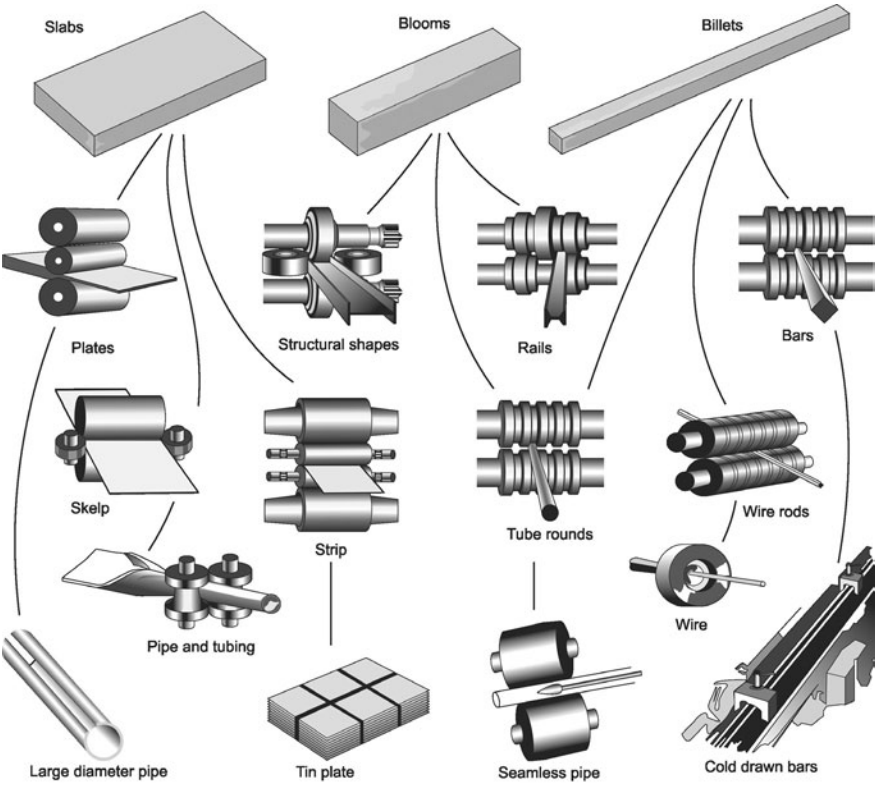


Fig. 1.2 Schematic flowchart for the production of various finished and semi-finished steel products which pass through rolling process

During cold rolling of flat products, the material is passed between two flat cylindrical rolls of the mill stand. Furthermore, various advanced techniques and systems are employed to keep the rolled material flat and the thickness of the finished product within close tolerance throughout the length and width of the product. These advanced techniques and systems have been discussed in Chapter 3 and 4 respectively.

1.3 Brief History of Rolling

1.3.1 The early history

It is a characteristic feature of engineering and technology that developments and innovations in different fields of engineering and technology are often not attributable to any single person, or a specific date, or even a single place, or country. Engineering and technological developments are induced by social needs, and are often result of many pioneers over a period of time and places. History of development of rolling technology is no different.

Rolling of soft metals like gold, silver and perhaps lead was first performed by goldsmiths for making jewelry. Hand driven rolls of about ½ inches (12.5 mm) in diameter were in use during the fourteenth century. However, the concept of a true rolling mill is first found as a sketch in the notebook of Leonardo da Vinci. There is no evidence that this was ever built.

Before the end of the sixteenth century, at least two mills incorporating basic ideas of rolling are known to have been in operation. In 1553, a Frenchman named Brulier, rolled sheets of gold and silver of uniform thickness for making coins. In 1578, a man called Bevis Bulmer, received a patent for operation of a two spindles slitting mill with series of disc cutters to slit flats into narrow strips.

As per record available, rolling of iron into thin flats was first done in Bristol, the UK in 1666. As per a pamphlet on 'British Iron Trade' published in 1725, all bars were made by hammering even at that date. By 1682, large rolling mills for hot rolling of ferrous materials were in operation near Newcastle, the UK. These mills were used for rolling bars into sheets, which were cut into square rods in slitting machines.

Hot rolling of ferrous material into thin sheets was practiced in many continental countries, but was monopolized by Germany from the beginning of the seventeenth century until Major Hanbury started production in Pontypool works in the UK sometime around 1720[1].

In 1728, a patent was issued to John Payne in England for producing different rolled shapes using grooved roll. However, there is no proof to support that such an idea was put to practice.

In 1766, John Purnell of England received a patent for grooved rolls and arrangement of driving both rolls in unison through use of coupling boxes and nut pinions. Until this time, rolls were driven individually by water mill.

During this period, the hot mills were evolving to the modern form. William Playfield's English patent filed in 1783[2] shows use for cast housings and one screw on each window for screw down.

By the middle of the eighteenth century, pack rolling came into practice for producing thin plates for tinning.

The eighteenth century also saw the advent of tandem mill in which metal is rolled in successive stands. Richard Ford's English patent in 1766 is the first record of a true hot tandem mill for producing wire rods. James Cockshutt and Richard Crawshay, about 1790, built a four-high tandem mill near Sheffield, the UK, with a capacity of 1 – 2 tons per day. Patents were obtained for tandem mill for rolling of plates and sheets.

The earliest record of a true continuous wide-strip rolling mill is that built in 1892 at Teplitz in Czechoslovakia[3] (then an Austrian territory) consisting of two three-high roughing stands and a finishing train consisting of five number two high continuous finishing stands. The two three-high train and the continuous five stand train was driven by 1000 H.P. steam engine each. Starting with 8″ (200 mm) thick steel slabs, the mill was reported to be producing sheets up to 50″ (1270 mm) wide strip of thickness between 0.08″ – 0.12″ (2 mm to 3 mm) and in length up to 60′ (18.29 m).

History of metalworking in the United States began with the arrival of colonists from Europe. The first American rolling mill was built in 1751 in Massachusetts. This was used for rolling 3″ (75 mm) wide and 3/4″(19 mm) thick hammered bar to 1/4″(6 mm) thickness suitable for slitting into nail rods, in 4 passes. In 1793 Isaac Pennoch established a rolling mill which by 1810 was rolling plates in mills with 16″ – 18″ diameter and 3 – 4 feet long rolls. In same plant around 1820, boiler plates were rolled by Dr. Charles Lukens (Pennoch's son-in-law).

The first rolling mill in America to have been powered by a 70 H.P. steam engine was built by Christopher Cowan in western Pennsylvania. In 1819, the first angle iron rolled in the US was produced at the Union Rolling Mill in Pittsburg. By 1825 five rolling mills were in operation in Pittsburg which eventually became focal point of metalworking industry. Rolling of corrugated plates was patented in 1850. After civil war ended in 1865, rapid expansion of railways gave a tremendous impetus to the American iron and steel making and rolling industry.

1.3.2 Modern steel rolling plants

Since the early twentieth century, rolling industry saw a continuous string of developments in terms of size and production capacity, new design of mill stands and ancillary equipment, increased working efficiency, greater instrumentation and automation for quality at higher mill speed.

The pioneering effort of Tredegar Iron and Coal Company of South Wales is worth mentioning. In 1905 Whitehead[4] decided to modernize the continuous hot mill operation. In one 8-hr shift, the mill could produce 103 tons of 8″ wide × 0.03″ (0.75 mm) thick material. The plant had continuous furnaces, electric cranes, flying shears to cut strip coming out from the mill at a speed of 3000 fpm (~900 mpm), specially designed coilers to coil at fast speed, and many other novel features.

Another milestone in continuous rolling of wide strip was achieved in the Butler plant established at the Columbia Steel Company of America, which went into production in 1926, designed and developed by Townsend and Naugle for over a period of 10 years. This plant[5] included, among others, annealing furnaces, long continuous pickling line, welding arrangement for joining coils for continuous operation, and other processing auxiliaries.

After successful operation of the Butler plant, a number of such integrated plants were erected in the UK and elsewhere. As per data on wide strip mills published by Davy and United Engineering[6] of the UK in 1960, the largest width capacity mill was a 108″ (2740 mm) mill in Voroshilov Works in Russia.

1.3.3 Modern non-ferrous rolling plants

Credit goes to the Revere Copper and Brass Company[7] of America for beginning to roll copper strip in a so-called continuous mill in 1926. In this plant 5″ thick × up to 36″ width copper ingot was hot rolled in a two-high reversing mill to about 3/16″ (4.75 mm) thick strip. This strip, after suitable pickling and cleaning was cold rolled in a 4 stand four-high continuous mill. The plant gradually introduced mechanized sheet conveying system. In Britain, Imperial Chemical Industries that has been rolling brass and copper even before the American company, put a highly mechanized plant in Birmingham in 1933. In 1949, the Scovill Manufacturing Company[8] in the USA erected one of the most modern brass-rolling plants in which continuous casting of brass ingots of 2.5″ (63.5 mm) thick and 29.5″(750 mm) wide and more than one ton weight were produced. The ingots were initially cold rolled to 0.415″ (10.54 mm) in eight passes with two inter-anneals in a massive two-high mill. The mill stand was equipped with quick roll changing facility and vacuum cup type stock lifting arrangement was introduced.

The first four-high mill[9] was installed and operated in the UK, in the nickel and nickel alloy rolling plant of Henry Wiggin and Co. by around 1932 for cold rolling of these strips.

With gradual increase in consumption of aluminum alloys from the third decade of twentieth century and specially during and after the World War II, a number of large and high speed hot and cold aluminum rolling mills were established.

Pioneer of aluminum rolling in Britain was the British Aluminium Company formed in 1894. By mid 1940s, they laid out a modern aluminum rolling plant at

Falkirk,[10] which included continuous casting units. Thickness of 8″(200 mm) and about one ton weight slabs were sawed, which were hot rolled, edge trimmed then coiled for annealing and further cold rolled in both two-high and four-high mills. The four-high stands using 20″ (508 mm) diameter work roll and 49″ (1245 mm) back-up rolls and driven by 1500 HP variable speed motor, and rolling 6′ (1829 mm) wide coils at 450 fpm (136 mpm) were built by Robertson of Bedford. This mill manufacturer, later known as Lowey Robertson's Engg. Company, played a significant role in the development of large and high speed aluminum strip and foil rolling mills with various modern features and quality control systems. The South Wales Rogerstone works of the Northen Aluminium Co. (Alcan Industries) installed one of the most modern plants operating in Europe in 1950. This plant included a three-stand, four-high cold tandem mill. In this mill, coil weighing 1.75 tons could be rolled to a maximum width of 54″ (1370 mm) and a reduction in thickness of 90% was achieved in one pass through the three stands. The speed of strip from the last stand was greater than 23 miles per hour (2024 fpm or 613 mpm). Similar mills with similar production methods and parameters were also established in America.

1.3.4 Modern cold rolling facilities

From 1930's, cold rolling of hot rolled steel strips became a process of prime importance. A comparative picture of width and thickness of strip that was cold rolled between 1923 and 1937 will make the point clear:

Year	*1923*		*1937*	
Strip width	22″ (560 mm)	10″ (254 mm)	90″ (2290 mm)	35″ (890 mm)
Minimum thickness	0.14″ (3.55 mm)	0.05″ (1.27 mm)	0.038″ (0.96 mm)	.01″(0.25 mm)

Typical strip mills built in the 1930's are three-stand 84″ wide tandem mill with about 20½″ diameter work roll, 56″ diameter back-up roll and driven by motors totaling 6850 HP rolling at speeds up to 540 fpm. Just before and after the World War II, four-stand tandem mills came into operation. However, since 1960's five-stand tandem cold strip mill for rolling ferrous alloys has become the industry norm.

Although most of the tandem mills employ conventional four-high stands, a unique tandem mill designed for rolling of stainless steel strips up to 50″ (1270 mm) wide commissioned in 1969 by Nisshin Steel Corporation at the Shunan Works[11] located in Nanyo, Japan, utilizes a train of 6 stands, whose first and last is two-high stand while the intermediate stands are multi-roll Sendzimir mills.

With limited market of stainless steel, silicon steel, and foil gauge copper alloys, single stand Sendzimir mills proved to be quite popular for rolling these materials.

In order to meet the demands of high strip quality along with high productivity (i.e., high rolling speed), substantial improvement has been achieved since 1960's in the mill instrumentation, controls and auxiliaries like introduction of Automatic Gauge Control, Flatness Control and improved Roll Coolant systems.

1.4 Deformation of Materials

1.4.1 Elastic and plastic deformation

Metals are crystalline solids in which atoms are arranged in a well-oriented pattern. In the absence of any external force in a metal crystal, let the distance between a pair of atoms be r_o. The equilibrium interatomic distance r_o is that distance at which the attractive and the repulsive forces are equal in magnitude. The slope of the repulsive force curve is always more than that of the attractive force curve at the point of intersection of the curve. Therefore the equilibrium is of stable nature. The net inter-atomic force varies with the atomic spacing in a manner shown in Fig. 1.3, the positive side signifying attractive force. Under the application of an external tensile force, the interatomic distance increases beyond r_o to maintain the equilibrium. If the external tensile force is of magnitude F, then the interatomic distance should be r_a so that the net interatomic force is an attractive force of magnitude F, to balance the external force. If r_a is not very much different (of the order of 5%) from r_o, when the external force is removed, the atoms attain their original positions. A similar behavior is also observed with an external compressive force (when $r_a < r_o$). This behavior is called the elastic behavior of a solid material, and the associated deformation is termed as *elastic deformation*.

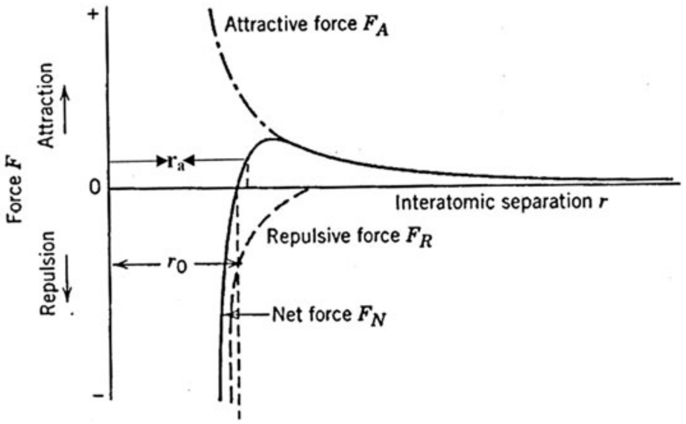
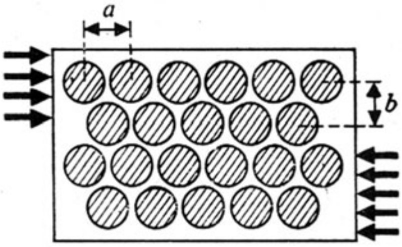


Fig. 1.3 Variation of net interatomic force with interatomic distance

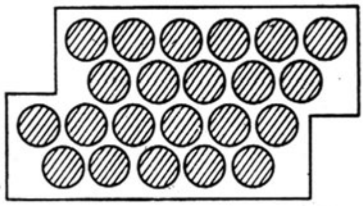
This phenomenon described for a pair of atoms is also true for normal solids on a macroscopic scale. It may be noted from Fig. 1.3 that the tangent to the curve at the point r_o coincides with the curve over a small range on either side of point r_o. This indicates that the external force is proportional to the change in the interatomic distance. Hence, within this elastic range, most solids follow a linear force deformation rule, and are thus called linear elastic solids.

Now, let us consider a crystal lattice of a solid material with regularly spaced atoms as shown in Fig. 1.4a. Under the externally applied shear force, the upper layers of atoms will move to the right and the lower layers will move to the left.

When the applied shear stress reaches beyond a sufficiently high value called the shear yield stress of the material, the crystal lattice takes the shape as in Fig. 1.4b. Here, all the atoms are again in equilibrium and will remain so if the external stress is removed. Thus, a permanent deformation is produced in the crystal lattice. This permanent deformation is termed as *plastic deformation* and cannot be recovered by withdrawing of the external stress.



(a) Original position of atoms



(b) Position of atoms after slipping through distance 'a'

Fig. 1.4 Scheme of plastic deformation in perfect crystal

The amount of shear stress to cause the deformation between two layers of atoms in a perfect crystal can be estimated. Referring to Fig. 1.5(a), the shear stress, τ, and the amount of displacement of the top layer, x, may be approximated by the relation:

$$\tau = \tau_0 \sin\frac{2\pi x}{a} \qquad 1.1$$

This variation is shown in Fig. 1.5(b). For small values of x/a, $\sin\frac{2\pi x}{a}$ may be approximated as $\frac{2\pi x}{a}$. Hence, the foregoing relation can be rewritten approximately as

$$\tau \approx \tau_0 \frac{2\pi x}{a}, \text{ where } \tau_0 \text{ is the ultimate shear stress}$$