METALS INDUSTRY

Metals, and especially iron, were some of the oldest materials processed by our ancestors. The commercial exploitation of iron ores began in central Europe about 1000 B.C. In the Middle Ages, iron was produced by directly heating a mixture of iron ore and charcoal in a small shallow pit dug in the ground and lined with clay. In these so-called bowl furnaces, the ore was reduced to a mushy mass of relatively pure iron including cinder and ash, and then hammered and forged into a finished product. Blast furnaces were introduced in Europe around the end of the fifteenth century. These furnaces were capable of continuously producing metal in much larger quantities. In the sixteenth and seventeenth centuries the output of blast furnaces was mostly in the form of pig iron for subsequent working at forges.

The operation of the forges remained essentially the same until 1784 when Henry Cort introduced the process of puddling and rolling iron. This process involved decarburizing pig iron to an appropriate carbon content by melting it directly in a puddling furnace and then passing it through rollers of special design. The top roll in Cort's process contained a properly shaped collar that was made to fit into a specially designed grove in the bottom roll. Using this mill, it was possible to produce iron bars at a rate ten to fifteen times faster than with tilt hammer technology, which predominated then.

The Industrial Revolution of the nineteenth century provided considerable impetus for the development of improved hot rolling processes for iron and also for other metals, such as aluminum. The development of the continuous rod mill did not begin until about 1870, and the length of the rod it produced was limited to less than 100 m. Yet, around the same time, the rapid expansion of the new electric telegraph required wire in the greatest possible length. The first reversing plate rolling mill and the first universal mill, which combined horizontal and vertical pairs of rolls in one stand, were placed in operation in the mid 1850s. During the second half of the century, considerable progress was made in mills for rolling structural shapes. Universal reversing mills for rolling Z-bars, H-beams, and flanged beams came into existence around that time.

Simultaneously with the progress in steel rolling, advancements were also made in steel conversion. The Bessemer converter was invented in 1857. This steelmaking process consisted essentially of blowing hot air under pressure through a bath of molten iron in a vessel. Initially, the Bessemer converter was lined with acid refractories and was used to refine iron that was high in manganese and low in phosphorus. In later years, the acid-based converter was continuously improved until the 1950s when oxygen, instead of hot air, was introduced to remove carbon from the hot metal. This new oxygen-based process was readily adapted for blast-furnace iron of medium to high phosphorus content. It was extensively used in the 1960s and 1970s, especially with the introduction of computers for automatically controlling the steelmaking process.

The rapid progress of the metals industry in the early part of the twentieth century included the development of the open-hearth and electric furnaces and major advancements in rolling and shaping of metals. This required an in-depth understanding of the fundamentals of metallurgy to improve metals properties and expand their usefulness. Open-hearth furnaces were very popular in the first half of the twentieth century and were the main producers of steel in the United States. However, since around 1970, production from open-hearth furnaces has been decreasing, and production from electric furnaces has been steadily increasing. In 1977, approximately 22% of the steel produced in the United States was melted in electric furnaces. The 1970s also witnessed considerable improvements in metal rolling technology. Larger, faster, and more powerful mills were being produced capable of rolling metals of larger sizes to closer dimensional tolerances and improved surface finishes. Factors that contributed to these improvements include changes in the mill housing, the availability of better rolls, more powerful drive motors, and enhancements in the instrumentation and control systems. Today's mills are more productive and are generally completely computer-controlled. For example, in a modern hot-strip rolling mill of the 1990s, the computer decides when a slab may be charged or discharged from the reheat furnaces. The computer also decides when the cooling system on the run-out table and coilers should be turned on or off to provide the desired finishing and coiling temperatures.

In the next several sections, we review some basic concepts associated with the metals industry, in general, with particular emphasis on the steel industry. The topics discussed include an overview of the steelmaking process, iron ores, furnaces, continuous casting machines, rolling mills, automatic gauge control, run-out table temperature control, ac/dc drives, and product quality.

OVERVIEW OF THE STEELMAKING PROCESS

The manufacture of steel products, or of metal products in general, is a complicated procedure that involves a series of sophisticated interacting operations (1,2). Figure 1 is a diagram of an oversimplified steelmaking process. This figure does not include the part that corresponds to the product processing lines, which is a continuation to the displayed process. The process line operation is illustrated in a different figure shown at the end of this section. Nearly all products made of steel today fall into the sequence of operations shown in Fig. 1.

Iron oxides, such as iron ore, are contained in iron-bearing materials. The blast furnace reduces the iron ore to molten iron, known as pig iron, by using charcoal or the carbon of coke as the reducing agent. During the process, approximately 3 to 4.5% of carbon is absorbed by the iron, which is subsequently processed to make cast iron. Modern day demands require steel to be produced at even further reduced carbon content on the order of less than 1%. To meet these requirements, today's steelmaking furnaces remove the excess carbon by employing controlled oxidation of mixtures of molten pig iron, molten iron, and scrap steel. Furthermore, while the carbon removal process takes place, the addition of certain chemical elements, such as, chromium, nickel, and manganese to the molten pig iron produces the so-called alloy steels. After the molten steel has attained the desired chemical composition, it is in liquid form and is poured into a ladle from where it is teemed down into a large mold and eventually forms into a solid structure, termed an ingot. Ingots are removed from the mold and taken to reheating furnaces, where they are uniformly reheated, before they are rolled into semifinished steel structures, such as slabs, blooms, and billets. Then semifinished steel is further processed in rolling mills to produce finished steel products.

Nowadays, most liquid steel is taken to continuous casting machines, where it is poured into the top of open-bottomed molds and then withdrawn continuously from the bottom of the mold in solid forms of various shapes and dimensions (1,2,4,5). After heat treating to attain certain mechanical properties, the slabs, blooms, and billets are subsequently mechanically processed in hot rolling mills, resulting in finished steel products (i.e., bars, plates, sheets, wires, rods, structural beams, and tubes). Moreover, these products can be used in their present form or further processed in cold mills, temper mills, forging, extruding, and so on, for additional surface and hardness improvement. If coating, pickling, tinning, annealing, or cleaning is necessary, the finished steel products are taken to the corresponding process line (1,2,19). Figure 2 is a schematic arrangement of a typical horizontal electrolytic cleaning line.

IRON ORES

It is well known that a significant percentage of the earth's crust (approximately 4%) is composed of iron. However, it needs to be processed to become suitable for use. The part of the iron-bearing material that could be processed and sold is called "ore." Iron ore is classified according to the processing requirements that transform it into marketable form. The ore's quality is characterized by the following chemical and physical properties:

Chemical: high iron content, low acid gangue content (i.e., combined silica and alumina), low phosphorus, low in deleterious elements, mainly sulfur, titanium, arsenic and the base metals, and low or free combined moisture

Physical: uniform size with particle diameter varying from 0.5 to 3 cm which contributes to higher blast furnace productivity

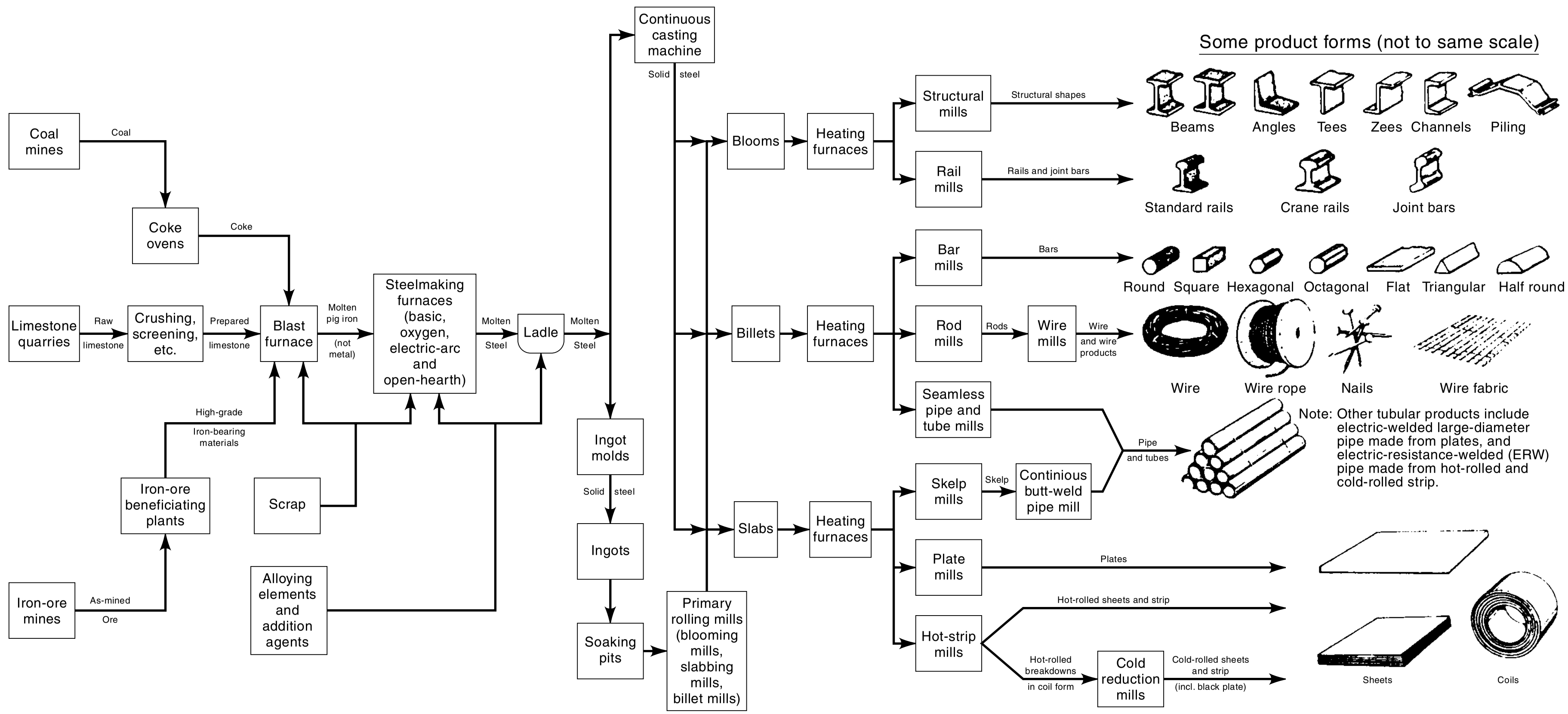


Figure 1. A flow diagram of an oversimplified steelmaking process (1).

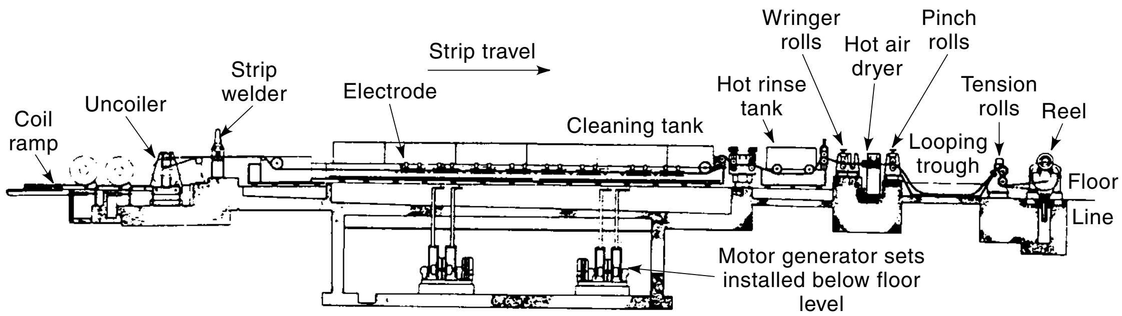


Figure 2. Schematic arrangement of a cleaning process line (1).

Before iron ore is fed to a blast furnace, it undergoes treatment to produce a more desirable blast furnace feed. This treatment, called beneficiation, may include crushing, grinding, screening, classifying, sintering, pelletizing, nodulizing, and concentrating.

FURNACES

Blast Furnace

A very simple description of a blast furnace operation is as follows: Ore is charged at the top of the furnace, and molten iron is tapped close to the bottom by incompletely burning fuel in combination with iron ore. In modern days coke is used as a fuel instead of charcoal. Heated pressurized air is supplied, promoting partial combustion of the fuel and evolution of carbon monoxide, generating heat in excess of 1900°F. Figure 3 shows a plant and an idealized cross section of a typical American blast furnace, respectively. The blast furnace is a tall shaft-type structure with a vertical stack superimposed over a crucible-like hearth. Iron-bearing materials are charged into the top of the shaft. At the bottom crucible of the shaft, directly above the hearth, there are openings, which introduce blasts of heated air and fuel. The injected fuel and the majority of the charged coke are burned by the heated air to generate the required temperature and reducing gas that remove oxygen from the ore. The reduced iron melts and runs down to the bottom end of the furnace's hearth. Flux and impurities in the ore combine to create a slag which in turn melts and accumulates on top of the liquid iron in the hearth. Both slag and iron are drained out of the blast furnace through tapping holes (1,2).

Open-Hearth Furnace

The open-hearth furnace employs a regenerative technique to generate the high temperatures necessary to melt the charged raw material, that is, the hot combustion products leave the furnace chamber through passages guiding them to checker chambers containing firebrick. The large brick area arrangement contributes to heat generation when it contacts hot gases. Part of the generated heat is transferred back to the brick. In the open-hearth furnace the charge is also melted on a shallow refractory hearth of molten metal by a flame passing over the charge so that both the charge and the roof are heated by the flame. Despite the unique features offered by the open-hearth furnace, it also has some major drawbacks, such as low productivity and high installation and maintenance costs. As a result, the electric-arc furnace and the basic oxygen process have largely replaced it. Figure 4 shows a typical vertical section across an open-hearth furnace (1,2,9).

Electric-Arc Furnace

Raw materials and scrap steel are charged into the electric-arc furnace and then melted via an electric-arc generated onto these materials in the furnace, thus, generating heat and high temperature which are important elements in the steelmaking process. The electric furnaces are designed to remove impurities as gases or liquid slags and to tap the molten steel into a ladle for further processing, as described previously in Overview of the Steelmaking Process. Although, there is a plethora of development in the electric furnace area, electric furnaces can be broadly categorized into two major types, arc furnace and induction furnace. However, the most practical and readily applicable types are (1,9)

Alternating current (ac) direct-arc electric furnaces
Direct current (dc) direct-arc electric furnaces
Induction electric furnaces

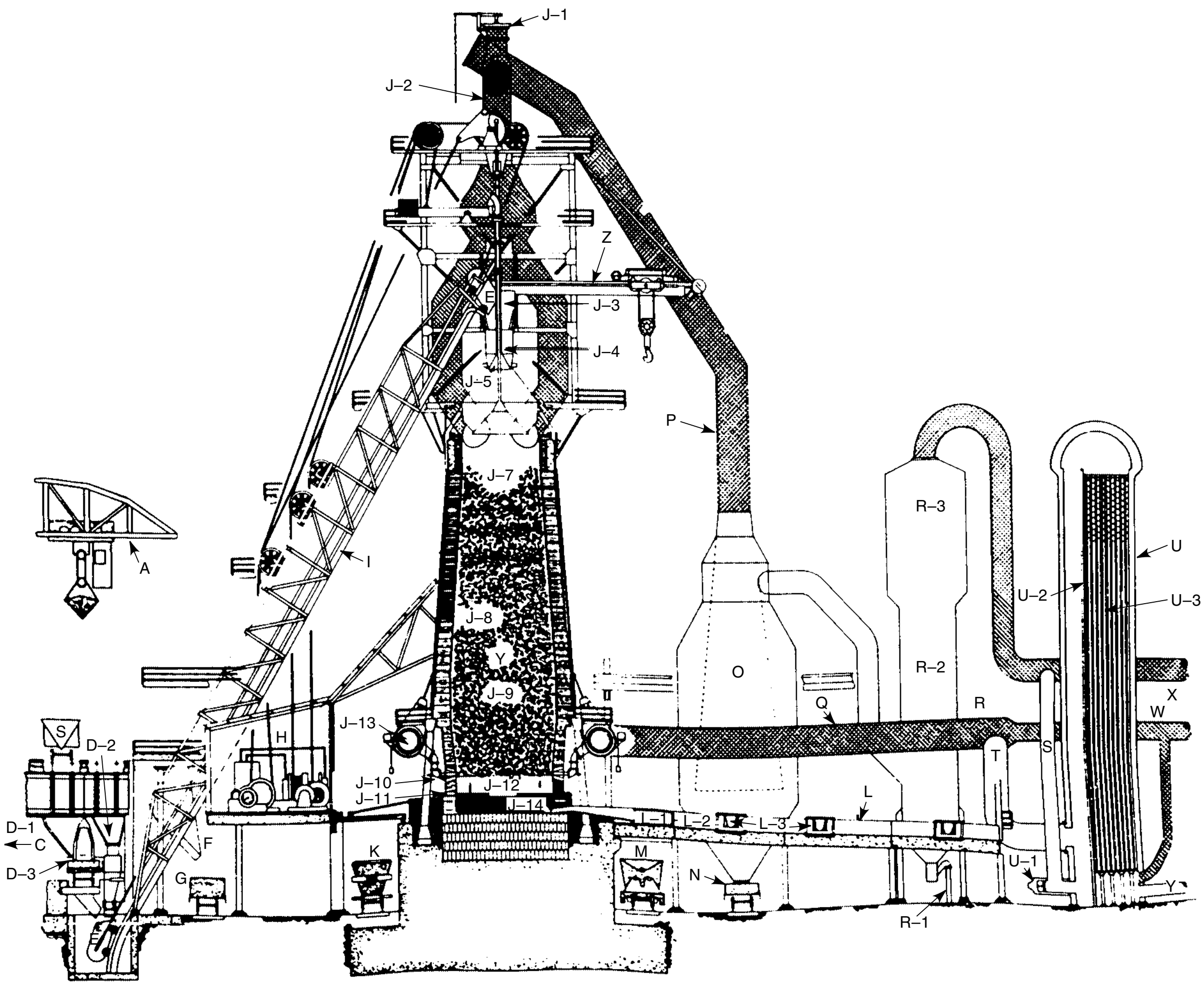
Electric heating is basically achieved in two ways, first, by current circulation through a medium and second by bombardment of a surface with a high-intensity electron beam. The latter method is not widely developed and has been applied only to low production capacities. Circulating current through an iodized gaseous medium or through a solid conductor generates enormous heat, which can be utilized to heat the steel. For completeness, we briefly mention some additional commonly known types of electric furnaces. These are typically named for the method of arc heating used, either indirect-arc heating or direct-arc heating. The direct-arc heating method is applied to both nonconducting and conducting bottom furnaces. Similarly, based on the method of resistance heating, furnaces are of the indirect, direct, and induction types. Figure 5 illustrates the cross section of an electric-arc furnace. In direct-arc furnaces, passing electric arcs from the electrodes to a metal charge circulates electric current through the metal charge, resulting in heat generation due to the inherent electrical resistance of the metal. The generated heat, along with the heat radiated from the arcs, constitutes the required furnace heat.

A fundamental difference between the ac and dc direct-arc furnace is that the former is designed with nonconducting bottoms whereas the latter has conducting bottoms. Nonconducting bottoms imply that the current passes from one electrode down through an arc to the metal charge and through an arc to another electrode. Conducting bottoms, on the other hand, means that current passes from an electrode through an arc to the metal charge to an electrode located in the bottom of the electric-arc furnace.

In induction electric-arc furnaces, electric current is induced in the metal charge via an oscillating magnetic field. The primary winding of a transformer is formed by inductors attached to the vessel, and the secondary winding is formed by a loop of liquid metal confined in a closed refractory channel.

CONTINUOUS CASTING MACHINES

Continuous casting caused the world steel production to skyrocket because of tremendous improvements in the efficiency



Legend

A. Ore bridge
B. Ore transfer car
C. Ore storage yard
D. Stockhouse
  D-1 Ore and limestone bins
  D-2 Coke bin
  D-3 Scale car
E. Skip
F. Coke dust recovery chute
G. Freight car
H. Skip and bell hoist
I. Skip bridge
J. Blast furnace
  J-1 Bleeder valve
  J-2 Gas uptake
  J-3 Receiving hopper
  J-4 Distributor
  J-5 Small bell
  J-6 Large bell
  J-7 Stock line
  J-8 Stack
  J-9 Bosh
  J-10 Tuyeres
  J-11 Slag notch
  J-12 Hearth
  J-13 Bustle pipe
  J-14 Iron notch
K. Slag ladle
L. Cast house
  L-1 Iron
  L-2 Slag skimmer
  L-3 Iron runner
M. Hot-metal ladle
N. Flue dust car
O. Dust catcher
P. Downcomer
Q. Hot blast line to furnace
R. Gas washer
  R-1 Sludge line to thickener
  R-2 Spray washer
  R-3 Electrical precipitator
S. Gas offtake to stove burner
T. Hot blast connection from stove
U. Stove
  U-1 Gas burner
  U-2 Combustion chamber
  U-3 Checker chamber
V. Exhaust gas line to stack
W. Cold blast line from blower
X. Surplus gas line
Y. Stock—Iron ore, coke, limestone
Z. Jib boom crane

Figure 3. A diagram of a plant and an idealized cross section of a typical blast furnace (1).

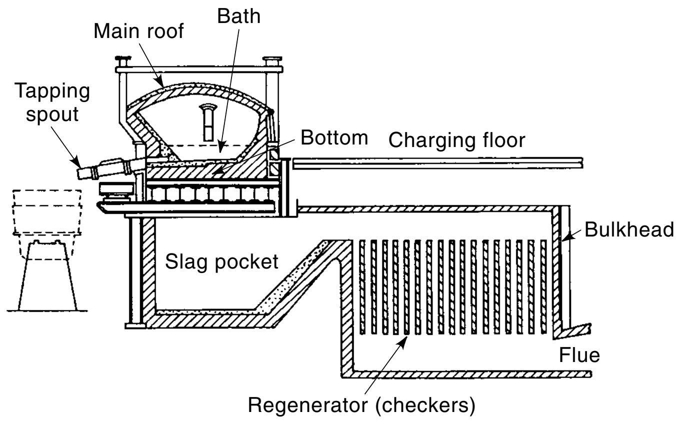


Figure 4. A vertical section of a typical open-hearth furnace (1).

of material utilization. A dramatic increase of more than 15% in process yield and significant improvements in product quality are attributed to the continuous casting process. For example, the process yield is better than 95% for continuous casting as compared with about 80% in ingot, slabbing, or bloom casting. In addition, other major benefits, such as significant energy savings, less environmental pollution and substantially reduced operating costs, are derived from the continuous casting process (1,2,4,5,9).

Casting machines are classified according to the product shapes they produce. It is important to mention that because of the advantages of continuous casting, the modern minimill concept (i.e., combinations of continuous casters with powerful electric-arc furnaces) has been extensively applied throughout the metals industry in recent years. There are four major categories to which casting machines belong, billet, bloom, round, and slab continuous casters. The major components of a continuous caster are illustrated in Fig. 6. The tundish is a reservoir for delivering liquid steel. The principal function of the water-cooled mold is to contain the liquid steel and initialize the solidification process. The secondary cooling system controls the cooling rate through a series of cooling zones associated with a containment section as the strand progresses through the machine. The function of the drive

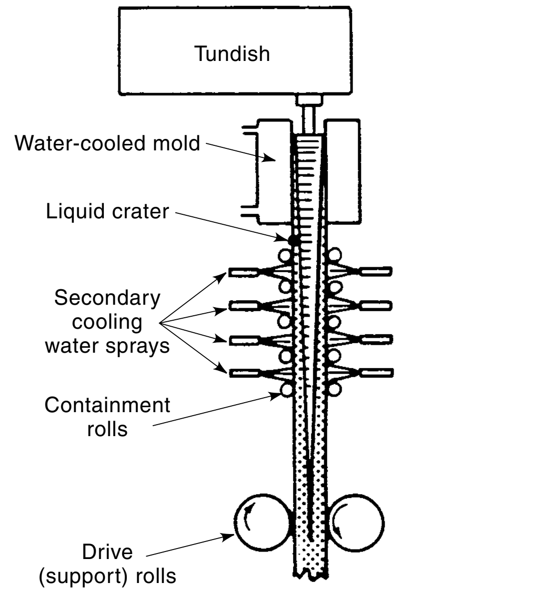


Figure 6. Major components of a continuous casting machine (1).

rolls is to support, bend, and guide the strand through a prescribed arc and the straightener, that is, from the vertical to the horizontal plane, as shown in Fig. 7. Note that there can be casting machines with multiple casting strands operating in parallel, each one having its own mold, secondary cooling water sprays drive rolls, and straightener.

The continuous casting process can be described as follows. Before starting the casting process, a long mechanical withdrawal system shaped like a slab, and known as the dummy bar, is inserted from the straightener (i.e., the horizontal plane) in the bottom of the mold to facilitate the initial extraction of the strand. Liquid steel is delivered in a ladle and poured at a controlled rate into the tundish. Nozzles guide the liquid metal flow in the bottom of the tundish so that the mold can be filled. When a certain liquid level limit in the mold is reached, the dummy bar, which is attached to the solidified metal, is withdrawn, pulling along the solidified cast. When the dummy bar exits the curved rack section, the

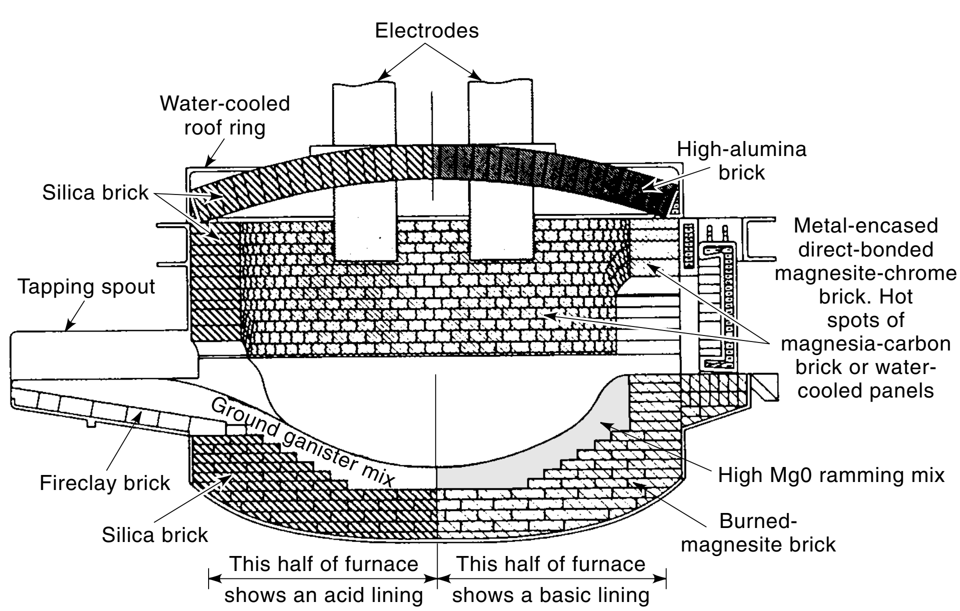


Figure 5. A cross section of a typical electric-arc furnace (1).

solidified metal is mechanically disconnected, removed, and cut to desired lengths.

ROLLING MILLS

Rolling mills are the workhorse of the entire metals industry. They are responsible for producing the largest percentage of finished metals (steel, aluminum, etc.) in many forms and shapes. A considerable number of various types of rolling mills exist today, but it is beyond the scope of this article to cover them all. Instead, we mention the most general classes of rolling mills and focus on those most widely used in the steel industry. The list of references at the end of this article provides a wealth of valuable and detailed information for the interested reader (1–3,6–12).

Many of the components, accessories, and systems of rolling mills are common to all types. They differ in design, performance, and operation to conform to the special conditions and specifications of a particular mill. Because most technical challenges, innovative solutions, and high performance specifications have been in the domain of flat product rolling, we refer to concepts and systems associated with this type of rolling mill with special emphasis on hot and cold strip rolling, such as automatic gauge control (AGC), run-out table (ROT) strip cooling, ac/dc mill drives, and product quality. In particular, we consider hot and cold strip mills because this area has experienced explosive research and development in recent years.

The following are basic components common to most types of rolling mills:

- work and backup rolls with their bearings
- mill foundation and housing
- roll balance system
- roll-gap adjustment system
- roll change system
- mill protection devices

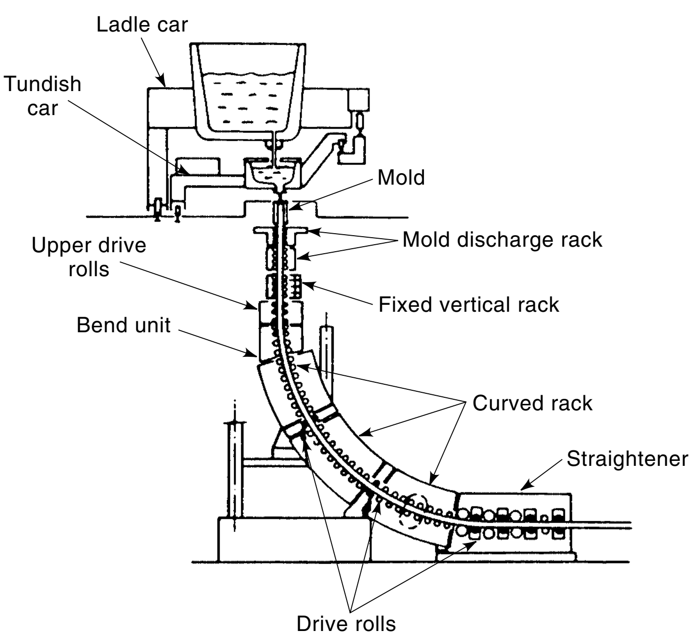


Figure 7. Cross section of a slab caster (1).

- roll cooling and lubrication systems
- drive spindles and coupling
- pinions and gearing
- drive motors and motor couplings
- electrical power supply and control systems
- idle and bridle rolls
- uncoiler and coiler systems
- coil handling equipment
- mill instrumentation, monitoring, and operating control devices

Figure 8 shows a small experimental rolling mill with most of the previously listed components identified. The most important component of a rolling mill is the mill stand and its associated auxiliary equipment. Figure 9 shows a typical mill stand arrangement. Mill stands are mainly categorized with respect to the rolling temperature, direction of roll axes, direction of rolling, main motor type, mechanical drive arrangement, and special design.

Roll arrangement types are based on the way the rolls are arranged. There are two, three, four, five, and six-high, cluster mill stands and mill stands with off-set rolls (see Fig. 10).

Direction of roll axes types include horizontal, vertical crossed-roll and mill stands with parallel tilted rolls.

Direction of rolling types include reversing, nonreversing, and back-pass mill stands.

Main motor type: The work and backup rolls of a mill stand are driven either by ac or by dc motors.

Mechanical drive train arrangement types include direct drive, gear drive, pinion stand drive, and independent drive. In addition, they can also be identified with respect to the type of driven rolls, that is, drive train with driven work rolls, backup rolls, and intermediate rolls.

Special design types: specially designed mill stands have been developed, such as planetary, rolling-drawing, contact-bend-stretch, and reciprocating.

In general, rolling mills can be classified in terms of rolling temperature, type of rolled product, and mill stand arrangement. For example, if the range of material temperature during the rolling process is between approximately 900° and 1300°C, then it is rolled in a hot rolling mill. Conversely, if the range is from 120° to 150°C, then it is rolled in a cold rolling mill. In warm rolling mills (for low-carbon steel), the material temperature is around 700°C. Finally, depending on the way mill stands are arranged a few more rolling mill types can be mentioned. For example, an open mill stand arrangement implies that the rolled piece is in one rolling stand at a time, whereas a close-coupled arrangement implies that the material is rolled simultaneously by more than one stand. In this latter arrangement, the stands must be appropriately speed-synchronized. Further types of mill stand arrangements include two very well known types, the universal and tandem rolling mills.

Hot Strip Mills

Figure 11 shows a multistand continuous hot strip mill. Slabs are heated in two or more continuous reheating furnaces. A

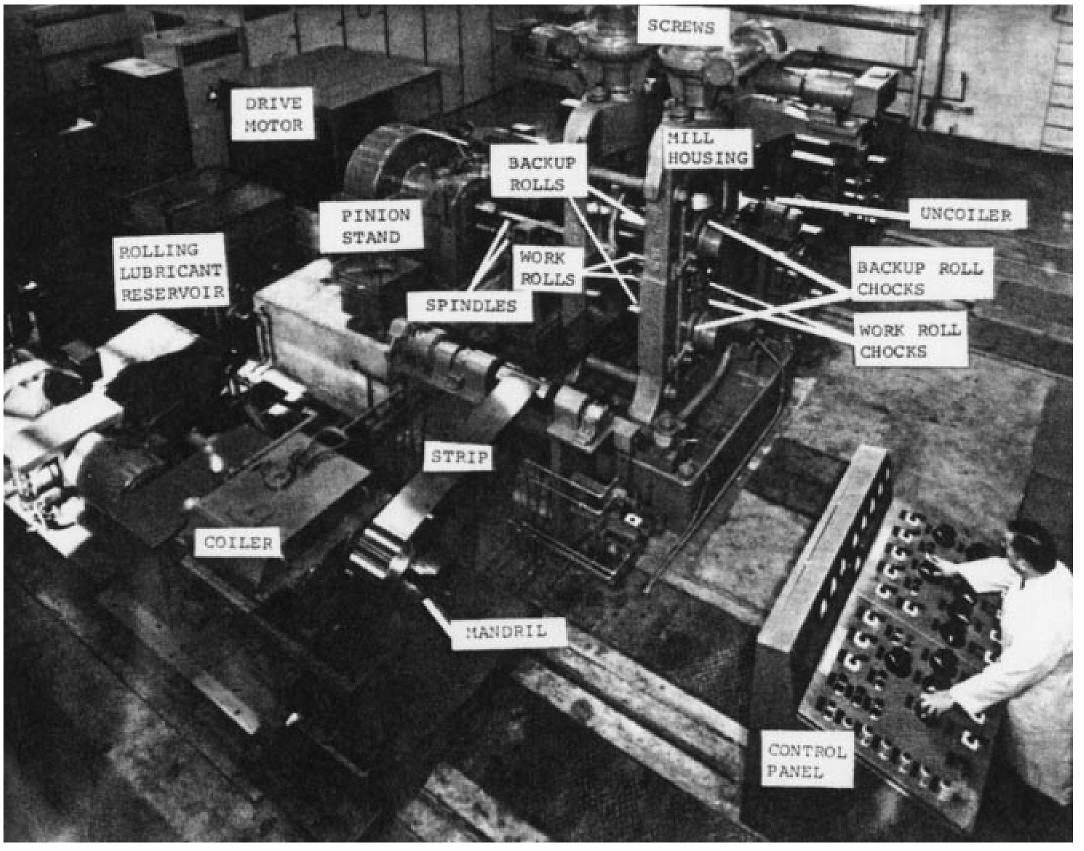


Figure 8. A picture of a small experimental rolling mill (7).

typical rolling train consists of a roughing scale breaker, one or more roughing stands, a finishing scale breaker, five to seven finishing stands, and one to three coilers. Driven table rolls convey the slab from furnace to the roughing mill and through the stands. Separating the roughing and finishing stands is a finishing table. High-pressure hydraulic sprays are located after the two scale breakers and after each

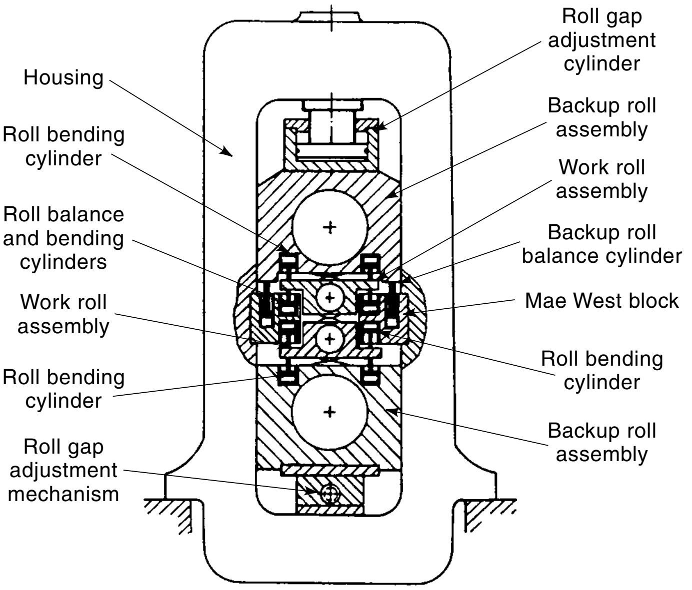


Figure 9. Arrangement drawing of a typical four-high mill stand (9).

roughing stand. As the steel exits the finishing mill, it crosses over a long table, consisting of many driver rolls, called a run-out table. On the run-out table, laminar jets or water sprays apply water to both top and bottom strip surfaces to reduce the strip temperature to a desired level before the strip is coiled. After cooling, the strip is carried to one of the coilers where it is wrapped into coils.

Mathematically, the operation of hot flat rolling can be described as follows (6,8–10): Given the distribution of normal pressure P_x in the deformation zone, we can determine the roll separating force P as (see Figs. 12 and 13):

$$P = \int_0^{l_d} P_x d_x = \int_0^{\alpha} RP_\theta d_\theta$$

where P_x is normal pressure at distance x from the exit plane, R is the work roll diameter, P_θ is the normal pressure at roll angle θ, l_d is the projected contact arc between the work roll and the material, and α is the roll bite angle.

If the entry and exit strip tensions are taken into account, an approximation of the roll separating force F is given by the expression

$$F = F_d(K_w - \beta_1 S_1 - \beta_2 S_2)$$

where F_d is the projected area of contact between the roll and the material, K_w is the material's resistance to deformation, S_1 and S_2 are the entry and exit strip tensions, and β_1 and β_2 are the entry and exit strip tension coefficients, respectively. The projected area of contact between the roll and the rolled

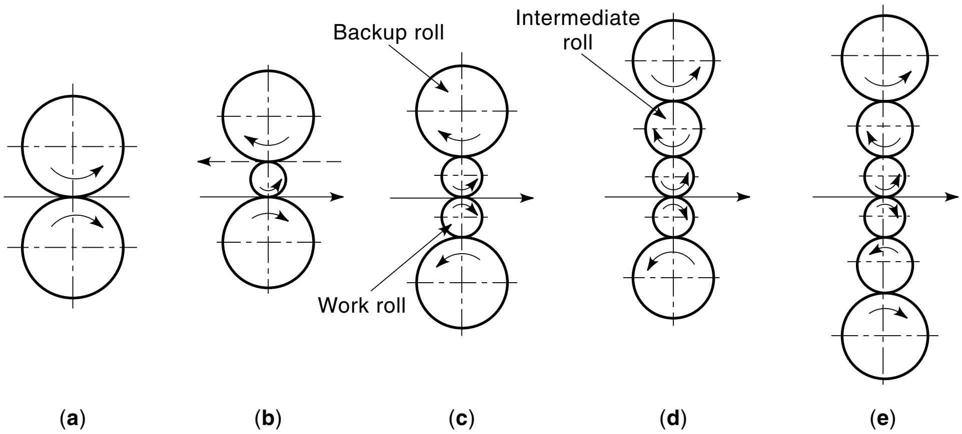


Figure 10. Types of roll arrangements in mill stands (9).

material is given by the expression

$$F_d = W l_d$$

where W is the mean width and l_d is the projected contact arc defined by the expression

$$l_d = \sqrt{R(h_1 - h_2) - \frac{(h_1 - h_2)^2}{4}} \approx \sqrt{R(h_1 - h_2)}$$

where h_1 and h_2 are the entry and exit thicknesses, respectively. The following relationship describes the mass flow through the roll bite:

$$V_1 h_1 = V_2 h_2 = V_\alpha h_\alpha = V h$$

where V is the workpiece velocity, h is the workpiece thickness at any point, and the subscripts 1, 2, and α denote entry, exit, and neutral points, respectively. Approximating the curve of spread with a parabola gives what is known as the parabolic mean width

$$w_p = \frac{w_1 + w_2}{3}$$

where w_1 and w_2 are the entry and exit workpiece widths, respectively. The strain rate differential equation can be written as

$$\frac{d\epsilon}{dt} = \frac{\Delta L}{L_0\,\Delta t}, \quad L_0 = L(0)$$

where ΔL is the change in length of a deformed body, Δt is the time needed to deform the body, and L_0 is the initial length. There are several proposed solutions to this differential equation, but we mention only Sims' solution without deriving it. For further details, the interested reader should con-

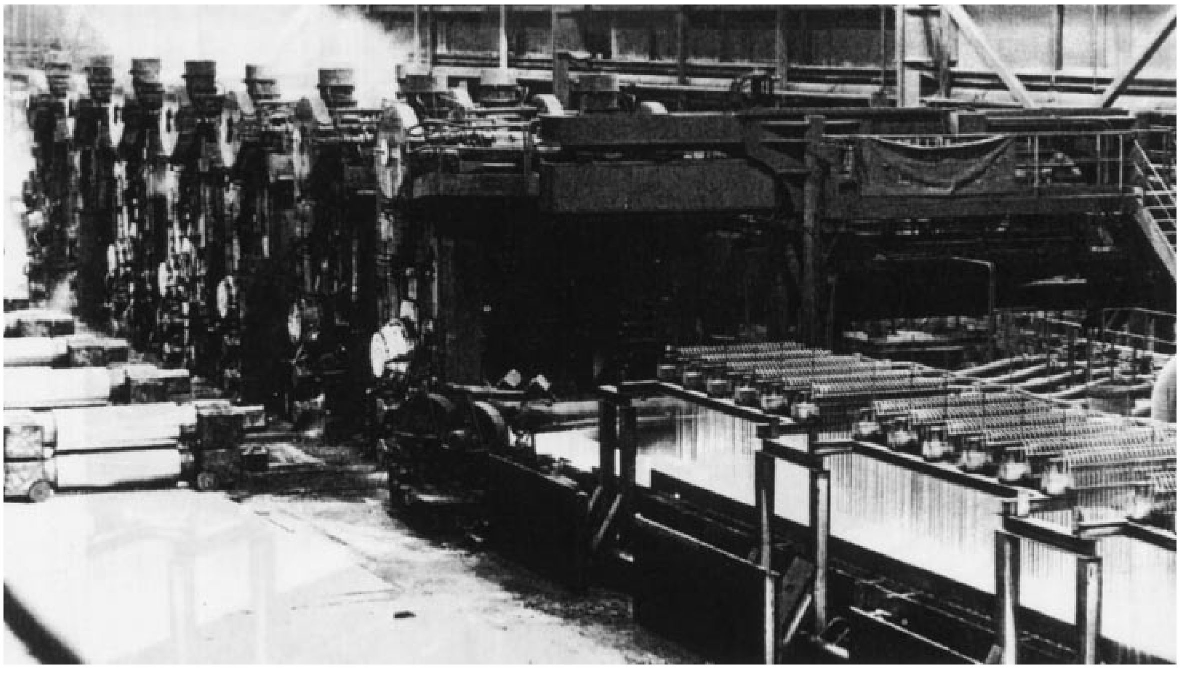


Figure 11. A multistand continuous hot strip mill (1).

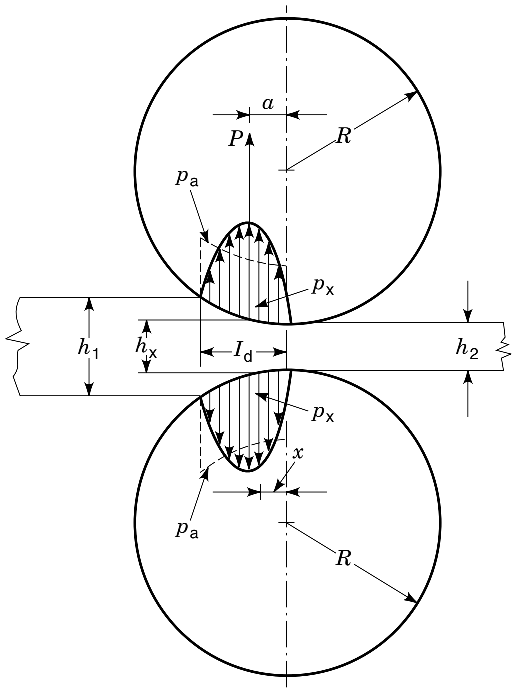


Figure 12. Distribution of normal pressure and rolling force (9).

sult Ref. 9. Sims' solution for mean strain rate is

$$\lambda = \frac{\pi N}{30}\sqrt{\left(\frac{R}{h_1}\right)}\frac{1}{\sqrt{r}}\ln\left(\frac{1}{1-r}\right)$$

where N is the rotational speed of the roll in rpm and r is the reduction which can be expressed as

$$r = \frac{h_1 - h_2}{h_1}$$

Cold Strip Mills

After hot rolling, the hot strip is wound into hot coils and the coils are further processed into what is called cold rolling or cold reduction. The hot-rolled coils are uncoiled, passed through a continuous pickle line, dried out, oiled, and finally recoiled. Oiling facilitates the cold reduction process and provides protection against rust. Cold rolling is done for one or a combination of the following three requirements: (1) to reduce thickness, (2) to harden and smooth the surface, and (3) to develop certain mechanical properties. After cold reduction, the cold strip goes through a cleaning and annealing process, and then it may or may not go through another cold rolling stage, known as temper rolling. The principal objective of temper rolling is to impart certain mechanical properties and surface characteristics to the final product. It is not intended to drastically reduce its thickness. Thickness reduction during temper rolling is most often less than 1% but may not exceed 10%.

It is interesting to note that the original purpose of cold rolling was to let the rolled material attain certain desired surface and mechanical properties. Reduction of thickness was of incidental importance. However, because thickness reduction in the hot strip mill is limited to no less than 1.2 mm, it is through cold rolling that ultrathin thicknesses of flat-rolled products can be achieved. A typical batch cold mill consists of an entry reel (payoff reel), multiple stand mill train, and an exit reel (tension reel). As the name implies, the coil is "paid off" (i.e., uncoiled) by the payoff reel, fed into the mill train, and recoiled on a mandrel at the exit side. A continuous cold mill, however, is directly coupled to a continuous pickle line, where the coils are continuously fed, so the payoff reel is not necessary.

Mathematically, the operation of cold flat rolling can be described as follows (7–9,11): Unlike hot rolling, where temperature is the germane variable affecting resistance to deformation, in cold rolling temperature is a function of work-hardening and roll contact friction. Furthermore, strip tension is a significant factor because it is of higher magnitude compared with hot rolling tension. As a result, the roll force and torque calculations differ from the corresponding calculations in hot rolling. Figure 14 illustrates elastic flattening of a cylinder on a plate. The length L of the region of contact is

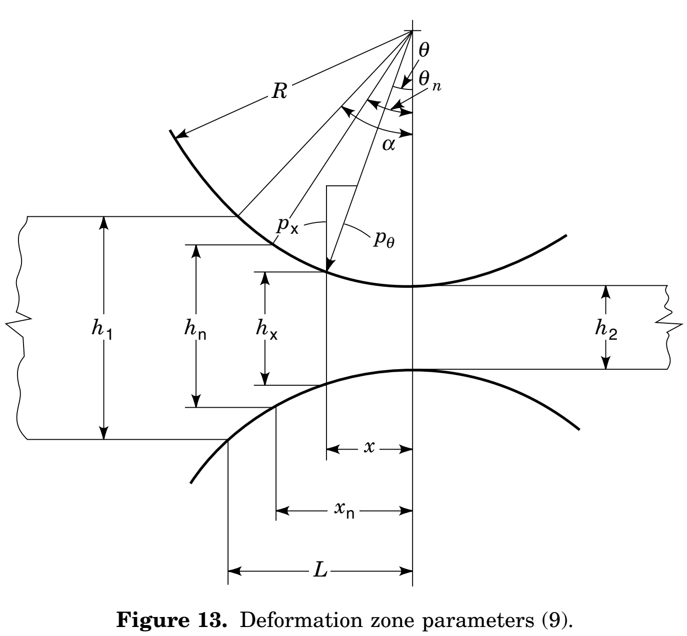


Figure 13. Deformation zone parameters (9).

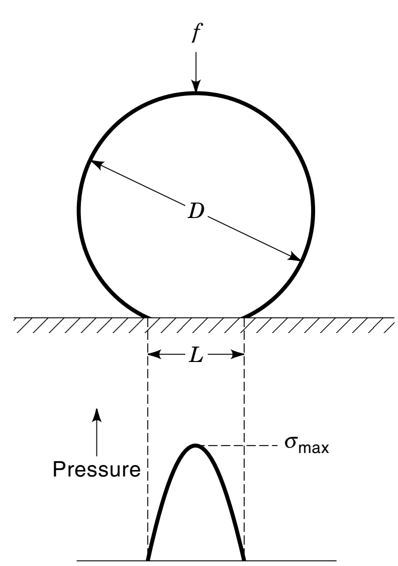


Figure 14. Elastic flattening of a cylinder on a plate (7).

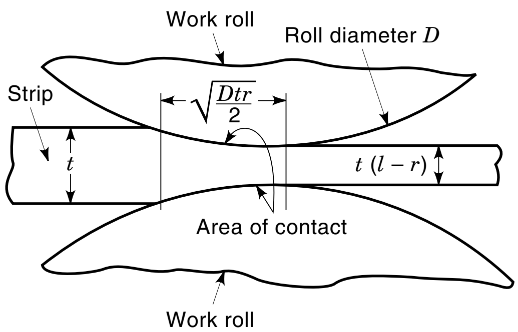


Figure 15. Length of contact arc for a rigid roll (7).

expressed as

$$L = 1.6\left[fD\left(\frac{1-v_1^2}{E_1}+\frac{1-v_2^2}{E_2}\right)\right]^{1/2}$$

where f is the force per unit length of the cylinder, D is the cylinder diameter, v_1 and v_2 are Poisson's ratio for the cylinder and plate, respectively, and E_1 and E_2 are the corresponding Young's modulus constants. The maximum stress at the center of the contact region is given by

$$\sigma_{\max} = 0.798\left[\frac{f}{D\left(\frac{1-v_1^2}{E_1}+\frac{1-v_2^2}{E_2}\right)}\right]^{1/2}$$

Figure 15 shows the length L of the contact arc for rigid rolls, which is given by the expression

$$L = \left(\frac{Dtr}{2}\right)$$

If the work rolls are not rigid, D should be replaced by the deformed roll diameter D_d, that is,

$$L = \left(\frac{D_d tr}{2}\right)$$

In the two previous expressions, t and r are entry thickness and reduction, respectively. The two diameters of iron work rolls are related by the following expression:

$$D_d = D\left(1 + 68\times 10^{-4}\,\frac{f}{\Delta h}\right)$$

where Δh is the draft, that is the reduction in strip thickness resulting from passage through the roll bite. There are many complicated mathematical models for calculating roll force and torque. However, here we consider only one without referring to details. SKF Industries (18) proposed the following formula for calculating roll force with strip tension:

$$F_T = F\left(1 - \frac{2T_{s1}+T_{s2}}{3S_m}\right)$$

where F is the roll separating force without strip tension, T_{s1} and T_{s2} are the entry and exit specific strip tensions, respectively, and S_m is the average yield stress of the compressed material. Assuming no entry and exit tensions and unit width, the specific total spindle torque (i.e., top and bottom) may be approximated by the following equation:

$$G_T = 0.5Dtr\sigma_c$$

where σ_c is the dynamic constrained yield strength of the strip in the roll bite. With this determined, the total torque that must be supplied to the mill stand is given by

$$G_{TW} = 0.5WDtr\sigma_c$$

Now, if entry and exit stresses due to tension are introduced, the forces acting on the strip result in the following expression for total torque (see Fig. 16)

$$G_{TW} = WDtr\sigma_c\left[r\left(1+\frac{\sigma_2}{\sigma_c}\right)+\frac{\sigma_1-\sigma_2}{\sigma_c}\right]$$

where σ_1 and σ_2 are entry and exit stresses due to tension, respectively. A very important parameter of flat processing of strip as it leaves the roll bite is what is known as forward strip differential v, defined by

$$v = \frac{(V_s - V_R)}{V_R}$$

where V_s and V_R are the strip and roll speeds, respectively. Assuming equal entry and exit stresses due to tension, then the relationship denoting the forward slip as a function of actual coefficient of friction μ and the minimum coefficient of friction μ_m can be written as

$$v = \frac{r}{r(1-r)}\left(1-\frac{\mu_m}{\mu}\right)^2$$

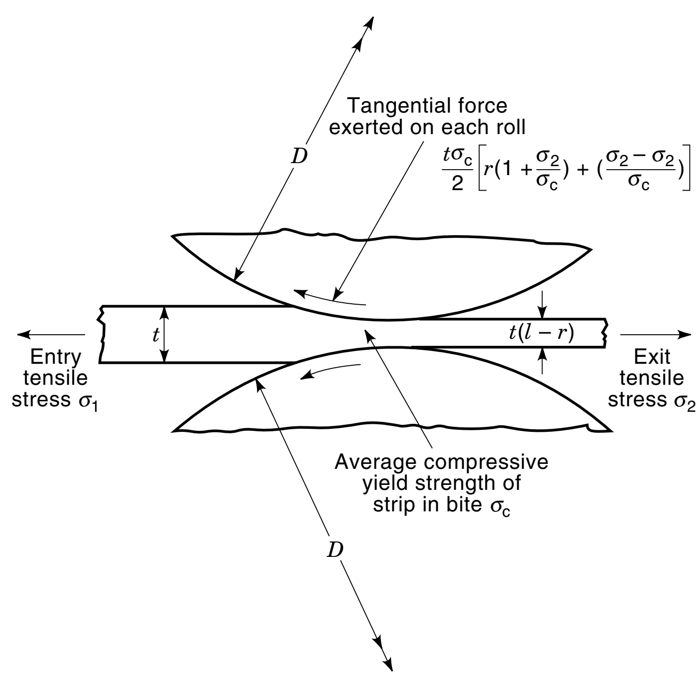


Figure 16. Tangential force on a roll surface (7).

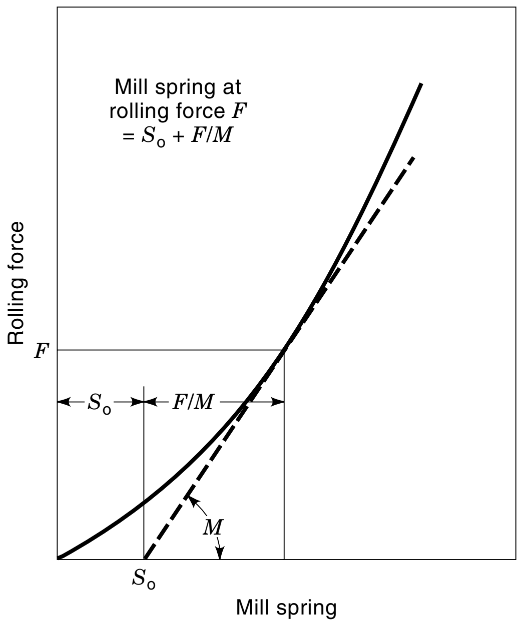


Figure 17. Mill-spring curve (8).

AUTOMATIC GAUGE CONTROL (AGC)

Measuring the thickness of a rolled strip accurately involves special, highly expensive, computer-controlled equipment, which applies various sophisticated measurement principles. Modern rolling mills for flat products are expected to deliver extremely high gauge performance under stringent tolerances. Factors that disturb the gauge of a rolled strip include strip tension, strip temperature, rolling speed, mill vibration, roll eccentricity, oil film in the roll bearings, thermal expansion and wear, and most importantly mill stand stretching. A well-known and widely used equation to analyze and synthesize the control systems to minimize gauge variations is referred to as the gaugemeter equation. It utilizes knowledge of the mill spring, obtained during mill calibration, rolling force, and the nominal position of the work rolls with no strip present. Assuming a no-load gap, then the roll gap h is expressed as (8,9)

$$h = s_0 + s + \frac{F}{M}$$

where s_0 is the intercept of the extrapolated linear position of the mill-spring curve, F is the total rolling force, and M is the mill modulus (see Fig. 17). The control system that regulates the material thickness to the desired value is called gaugemeter automatic gauge control (AGC). It is also sometimes refered to as BISRA compensation named after its developers. Figure 18 depicts an oversimplified block diagram of such system, and its equation is

$$s = h - \frac{F}{M} - \{\textit{other higher order compensations}\}$$

In this "gaugemeter mode," the mill is considered to be a spring that stretches according to the rolling load. Then the stretch of the mill is added to the unloaded roll opening to provide a measure of material thickness in the roll bite. The relationship between load and stretch is defined by the mill stretch curve, which is automatically measured during roll gap calibration. Because this curve is measured with full-face roll contact, bending of the rolls is not included in the basic curve. Therefore this curve is further adjusted for the roll diameters and strip width to ensure the most accurate estimate of centerline thickness.

During rolling in gaugemeter mode, the required on-gauge cylinder position reference is continuously calculated by using the gaugemeter equation and is issued to the position control loops. This reduces gauge variations due to mill stretch variation with changes in force. In principle, this makes the mill appear stiff in maintaining a constant loaded roll gap. The delivered gauge closely follows the loaded roll gap and therefore is also held nearly constant.

RUN-OUT TABLE TEMPERATURE CONTROL (ROT)

Temperature control of hot rolled strip has always been of great interest in the steel/metals industry. The cooling process is directly correlated to the grain structure formation of the product to be cooled. The grain structure defines the mechanical properties of the strip which in turn dictate the temperature requirements (1,2,6,12). It has been shown (13) possible to obtain algorithms that achieve uniform temperature throughout the material at a specified target temperature within tight tolerances. Such algorithms based on two-point boundary problem and dynamic programming theory minimize the temperature error with respect to a target temperature.

Two linearized models describe the system. Temperature loss due to radiation is given by

$$\Delta T_{\mathrm{r}} = \frac{CA_{\mathrm{r}}}{V_{\mathrm{r}}}\,[(T+460)^4 - (T_{\mathrm{a}}+460)^4]\,t_{\mathrm{r}}$$

where

$$C = \frac{s\xi}{\rho(T)c(T)}$$

s is the Stefan-Boltzmann constant, ξ is the emissivity, A_{r} is the surface area of a body subjected to radiation, T is the material temperature in °F at time t, T_{a} is the ambient temperature in °F, ρ is the specific gravity of the rolled material, V_{r} is the body volume, c is the specific heat of the rolled material, and t_{r} is the time interval of radiation.

The linearized model describing temperature change due to cooling water is

$$\Delta T_{\mathrm{d}} = \frac{2k}{\rho(T)c(T)h}\,(T - T_{\mathrm{w}})\left[\frac{\Delta l}{\pi\,\mathrm{a}v}\right]^{1/2} t_{\mathrm{w}}$$

where k is the thermal conductivity of the surface layer, h is the material thickness, Δl is the water contact length, a is the thermal diffusivity, v is the material velocity, T is the material temperature, T_{w} is the water temperature, and t_{w} is the water contact time.

Using these models, both dynamic programming and feedforward algorithms can be used to calculate the coiling temperature on the ROT, before the strip is delivered to the coiler. The difference is that the former performs better than the latter.

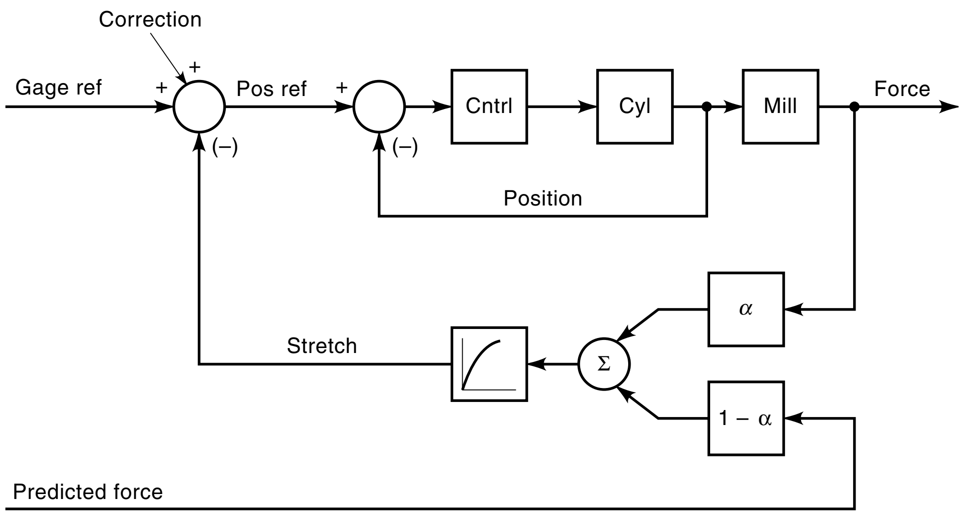


Figure 18. Block diagram of a gaugemeter AGC system.

The resulting boundary temperature T_2 can be written as

$$T_2 = T_1 - \sum_{i=1}^{N} \Delta T_{\mathrm{r_i}} - \sum_{i=0}^{N-1} u_{i+1} \Delta T_{\mathrm{d}_{i+1}}$$

where

$$u_{\mathrm{i+1}} = \begin{cases} 1 & \text{if} \quad \Delta T_{\mathrm{d}_{i+1}} \le \Delta T_{\mathrm{w}_i} \\ 0 & \text{Otherwise} \end{cases}$$

and ΔT_{w_i} is the temperature that needs to be lost by turning the water sprays ON. The dynamic programming algorithm solves a set of recursive difference equations:

$$T_{k+1} = a_k T_k - b_k \Delta T_{\mathrm{d}_k}, \quad k = 0, 1, \ldots, N-1$$

with the following corresponding cost function:

$$J = \alpha T_N^2 - \sum_{k=0}^{N-1} \beta \Delta T_{\mathrm{d}_k}^2$$

where a_k, b_k, α, and β are appropriate coefficients.

AC/DC DRIVES

DC Drives

Mill stands and other major associated moving components of a rolling mill require variable speed drives to control the dc motor speed. The dc drives are connected to an ac power line and apply controlled voltage to a dc motor at the load. As a result, some means of ac to dc conversion is necessary. The theory of converters/inverters is a broad and exceedingly complex subject (14–17).

In general, the basic characteristic of an all ac to dc converter is that its voltage source comes from an ac line, and that causes what is known as natural commutation. If the direction of power flow is from a dc source to an ac load, then the power converter is an inverter. In contrast to naturally commutated converters, the inverters used in dc drives are force-commutated unless the load has a leading power factor. Conceptually, the inverter can be thought of as a group of switches that connect the load to the dc bus and then alternate the polarity of the connections in a regular cycle. In large inverters, various types of power electronic semiconductor devices are used as switching components. Most such devices suffer from a serious limitation called forced-commutation, which occurs during the on-off switching process. What is known as a four-quadrant converter, or dual converter, can operate with both positive and negative polarities of both voltage and current at the dc bus. As a result, the dc motor can be driven and braked regeneratively in both forward and reverse directions. Figure 19 shows a simple six-pulse bridge converter with its waveforms. The speed of a dc motor can be adjusted by adjusting the armature voltage or by controlling the motor field. The drive is inherently of a constant horse-

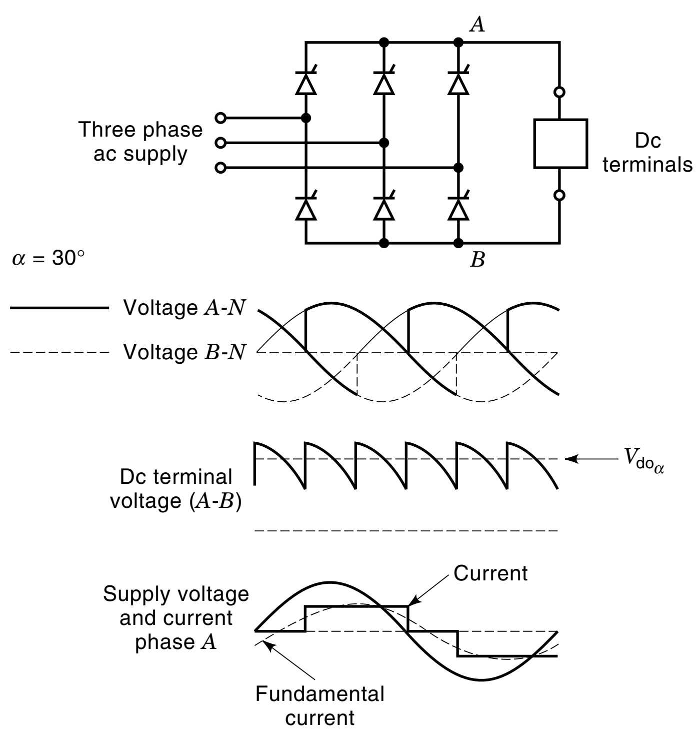


Figure 19. A simple six-pulse bridge converter with its waveforms (16).

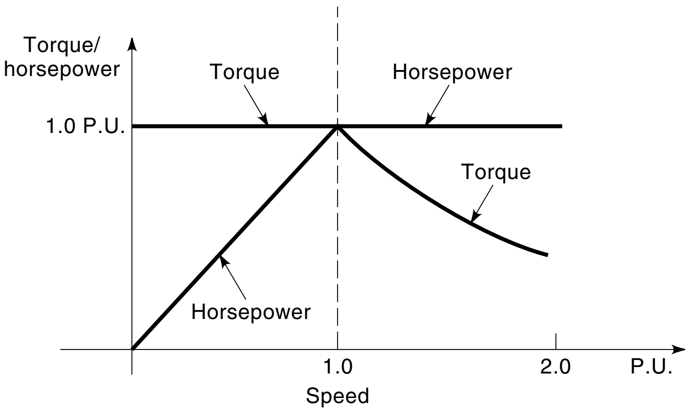


Figure 20. Torque/horsepower vs. speed for an adjustable-speed dc motor.

power type if the speed range of a dc motor is covered by its field control, that is, the torque varies inversely with the speed. Alternatively, if the dc motor speed range is covered by armature voltage control, the drive is inherently of a constant horsepower type, that is, the horsepower varies proportionally with speed. The steady-state voltage characteristic V_t of a dc motor can be expressed as follows:

$$V_t = R_a I_a + E + V_B$$

where R_a and I_a are the armature resistance and current, respectively, E is the counter emf voltage and V_B is the voltage drop at the commutator brushes. The steady-state Torque T can be expressed as

$$T = K\Phi I_a$$

where K is the motor torque constant and Φ is the air gap flux (i.e., per unit of full field value). The previous equation it shows that the torque delivered by the motor is directly proportional to the armature and field current.

The speed of the motor N can be expressed as

$$N = \frac{E}{K_E \Phi}$$

where K_E is the counter emf constant, lumping together certain design parameters, such as number of turns and connection type. The previous equation states that the speed of a dc motor is directly proportional to the counter emf and inversely proportional to the motor field. Considering the horsepower equation

$$\text{HP} = \frac{(\text{rpm})T}{5250}$$

and the steady-state characteristics, we can obtain the torque/horsepower versus speed characteristic of an adjustable speed dc motor, as depicted in Fig. 20.

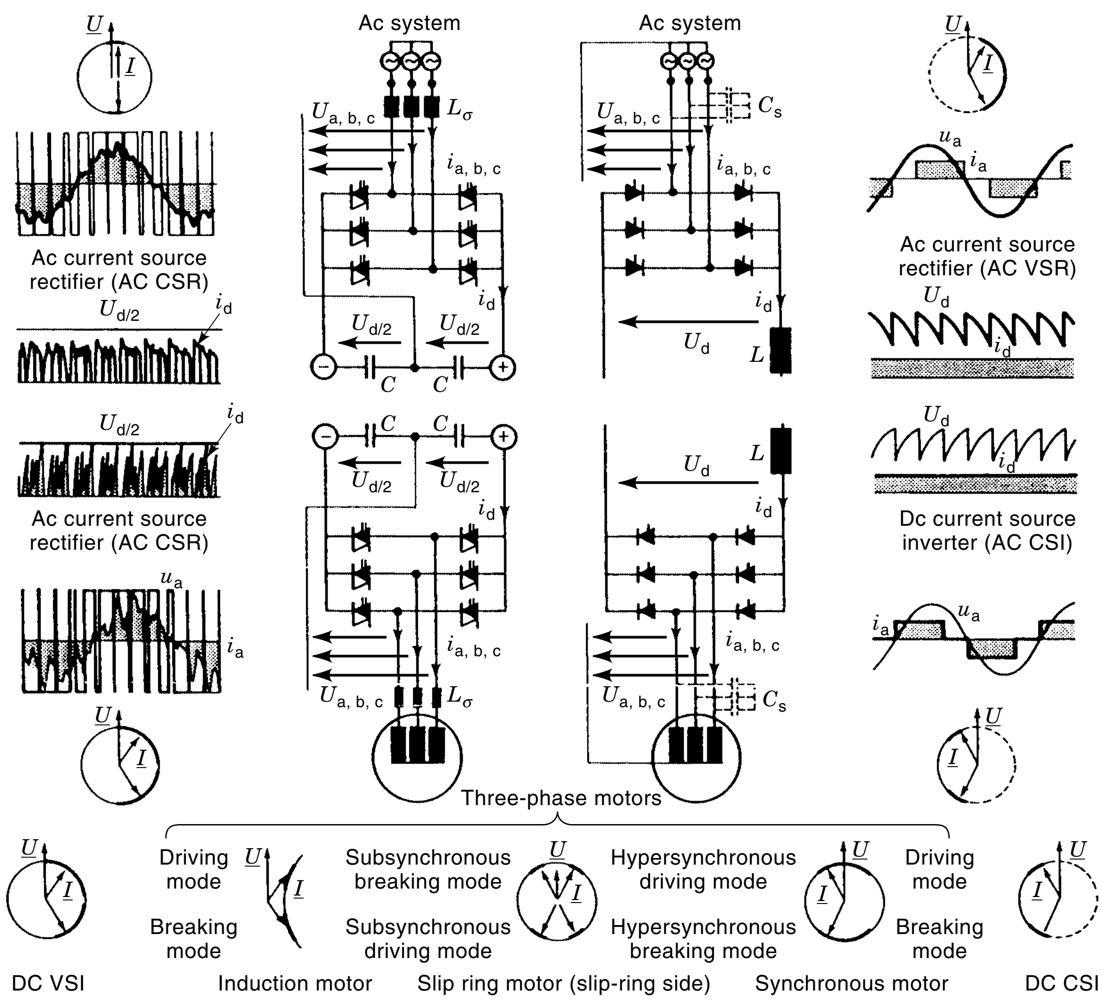


Figure 21. Ac voltage source rectifier and dc voltage source inverter circuits (14).

Ac Drives

For technical and economic reasons, the industry trend in recent years has been to replace dc drives with their ac counterparts. First, ac motors are more robust, reliable, and require less maintenance than dc motors. Secondly, ac drives save energy and provide increased motor output. Finally, ac motors are smaller in size for a given rating compared to dc motors, hence, are more cost effective. However, it should be mentioned that the high upfront cost of ac drives is offset by much lower lifecycle costs due to low maintenance and lower energy consumption. For these reasons, ac drives are the preferred choice.

The main types of variable speed ac drives used in rolling mills today, although rapidly changing, are cyclo converter current and voltage source drives. There are five main types of power semiconductor devices used to implement the bridges in the drives. These are (1) normal thyristors using natural commutation, (2) fast thyristors with forced commutation, (3) gate turn-off thyristors (GTO), (4) gain transistors (BJT) and (4) insulated-gate bipolar transistors (IGBTs) (14,15)

Converters are used to connect the ac power system to the motors and to convert the voltages and currents of the ac system to meet the motor requirements. In addition, they control the power flow from the ac system to the motors in the driving phase, and conversely they control the flow from the motor to the ac power system in the regenerative or braking phase. Figure 21 shows the ac voltage source rectifier and dc voltage source inverter circuits of converters used in large drives. The ac voltage source rectifier rectifies an impressed ac voltage and generates a switched dc voltage. However, a dc current source inverter, as the name implies, also inverts an impressed dc current and generates a switched ac current. The dc voltage source inverter, inverts an impressed dc voltage and generates a switched ac voltage, and at the same time it is also an ac current source rectifier, that rectifies an impressed ac current and generates a switched dc current, which, however, is not so common.

PRODUCT QUALITY

Product quality is of prime importance in every process of any metals industry. For the final product to be of high quality, each particular process in the industry must meet its specific quality requirements. Otherwise, the succeeding process might not be able to achieve maximum performance and/or product quality, resulting in economic loss. For example, a consistently well-proportioned coal blend is essential to produce the highest quality, ultimately uniform coke from the supplied coals, which in turn contributes to maximized blast furnace performance.

A major objective in the production of high quality steel in the secondary steel process is appropriate degassing of the gases (mainly, oxygen and hydrogen) that the liquid steel absorbs from the steelmaking material and the atmosphere. Continuous casting should be able to deliver good surface quality of the cast with minimum shape variations. Of equal importance are metallurgical qualities, such as minimized variability of chemical composition and solidification characteristics.

Performance objectives, and in particular how to achieve them in rolling mills, is a very interesting and challenging problem of enormous importance. In addition to the references mentioned (4,11,12), nearly all yearly proceedings of the Association of Iron and Steel Engineers (AISE) provide a wealth of information. The primary performance definitions in rolling mills, particularly flat rolling, are gauge, shape, cross-sectional profile, and width tolerances. One of the main reasons why a rolled product may not conform to the required tolerances of these three parameters is temperature variation in both transverse and longitudinal directions. The causes of temperature variations are many and include reheat furnace problems, poor surface quality of the slabs delivered from the caster, improper operating practices, and excessive edge radiation. It is an industry standard to have different sets of performance requirements for steady-state and nonsteady-state (i.e., accelerating, decelerating) conditions. Naturally, tolerances during transient conditions are usually relaxed. In addition, quite often, the tolerances differ for the head-end, the body, and the tail-end of the rolled piece. There are innovative solutions for optimizing various conditions that enhance performance, for example, optimizing mill configuration, operating parameters, and practices.

In the 1990s many sophisticated computer-based tools and technologies have been developed to monitor, identify, analyze, and eventually correct one or more special problems in any metals production process. Such software tools include automatic recognition of "out-of-control" features in critical process variables, rule-based diagnosis of special causes, a model-based search for symptoms where a diagnosis is not possible, and automated reporting of special problems (20).

Statistical process control methods (SPC) have been used to limit process variability and thus to produce higher quality products (21). SPC methods are intended to identify a variation in a process signal that differs significantly from the usual variability of the process. The statistical process control model assigns such a variation to special causes (i.e., a collection of charts), events that are not part of the normal operation of the process. Such events might include material changes, equipment failures, operator error, or environmental changes. Figure 22 illustrates a special cause management

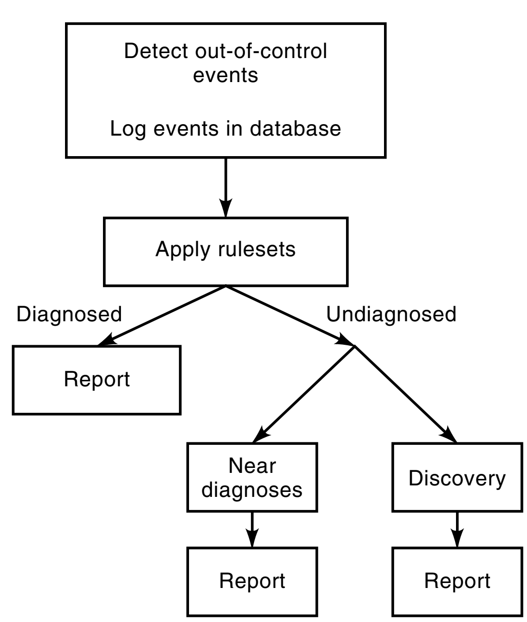


Figure 22. Special cause management block diagram.

block diagram of a statistical process control system. Process instabilities and abnormalities can also be diagnosed and their causes identified with knowledge-based procedures that automatically recognize primitive variations or changes by observing process signals (22).

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METASTABILITY. See CIRCUIT STABILITY OF DC OPERATING POINTS.