CHAPTER 20

Production of Semi-Finished Steel By Ingot Casting and Rolling

Introductory—This chapter starts with the liquid steel after steelmaking and ladle refining and follows it through a series of steps involving solidification to ingots (Section 1); rolling to semi-finished form of blooms, slabs, and billets (Section 2); and finally conditioning and cooling to prime semi-finished steel (Section 3).

SECTION 1

STEEL SOLIDIFICATION

INGOT SOLIDIFICATION

Ingots—After a heat of steel is properly refined either in an oxygen-steelmaking furnace, an open-hearth furnace, or an electric furnace, the liquid steel is tapped into a refractory-lined open-topped vessel called a steel ladle. Alloying materials and deoxidizers may be added during the tapping of a heat. The steel ladle has an off-center opening in its bottom, equipped with a nozzle. Some ladles are equipped with a stopper-rod assembly and a mechanism called the ladle rigging for raising and lowering the stopper rod vertically to open and close the bottom hole. Other ladles employ a sliding gate mechanism by which the flow of steel from the ladle can be controlled externally by sliding a refractory plate with an opening to align the opening in the plate with the opening in the ladle bottom to permit steel to flow; flow can be stopped by sliding the plate so that the solid part of the plate covers the bottom opening. The ladle is moved by an overhead crane to a pouring platform where the steel is then poured or teemed into a series of molds of the desired dimensions (Figure 20—1). The steel solidifies in each of the molds to form a casting called an ingot. During the course of solidification and cooling, the surface of an ingot is colder than its interior. In fact, for some types of steel, the centers of ingots are still molten during the subsequent stripping operation, in which the molds are removed from the ingots (Figure 20—2). For other types they are permitted to stand for a period of time to ensure solidification before leaving the teeming area.

The stripped ingots are placed in a tightly covered soaking pit. The “track time” between stripping and inserting the ingots into the pits should be minimized to conserve energy. The soaking pit is equipped with fuel burners to supply heat to the pit when necessary. There, the ingots are heated to the desired temperature for rolling and held a suitable time at that temperature (“soaked”) so as to equalize the temperature throughout the cross-section of the ingots. Modern soaking pits are, in reality, special heating furnaces, as described in Chapter 24. However, in early steel-processing practices, the soaking pits functioned differently. It was the custom at that time to strip the ingots from the molds as soon as possible after pouring and to place them in tightly covered holes or pits in the ground, where the heat from the interior (sometimes molten) of the ingot was conveyed to the relatively colder surface. This procedure not only equalized temperature throughout the ingots, but also supplied heat to the pits so that, with careful manipulation, ingots could be heated and maintained at the proper rolling temperature. This early process was called soaking; hence the designation soaking pits.

Following these reheating operations, ingots are rolled in primary mills to semifinished steel shapes (slabs, blooms, billets, etc.). The more modern technology of continuous casting (see Chapter 21) replaces all these ingot casting, heating, and rolling operations by casting semifinished steel directly. Continuous casting is increasing rapidly; however, today in the U.S. (and in the world), most steel is still cast by the ingot route.

Ingot Characteristics—An ideal ingot would be one
that was homogeneous both physically and chemically. It would have a fine, equiaxed crystal structure, and would be free of chemical segregation, nonmetallic inclusions, and cavities. Unfortunately, the natural laws that govern the solidification of liquid metal operate against attainment of the ideal condition and, instead, ingots develop within their interiors the well-known phenomena of pipe, blowholes, chemical segregation, nonmetallic segregation, columnar crystal structure, and internal fissures. Added to these manifestations of internal non-uniformity are detrimental surface occurrences such as ingot cracks and scabs. For a proper understanding of such phenomena, a brief description of the mechanism of ingot solidification is warranted.

Types of Ingot Molds—Ingot molds that are in common use are tall box-like containers made of cast iron and weigh from about 1 to 1.5 times as much as the ingots that are cast in them. The mold cavity for receiving molten steel is usually tapered from the top to the bottom of the mold, primarily to facilitate stripping of the ingot. As shown in Figure 20—3, the taper gives rise to the two principal types of molds: big-end-down, and big-end-up. The big-end-down molds are further classified as open-top and bottle-top; the big-end-up molds as open-bottom, closed-bottom, and plug-bottom. Some big-end-up ingot molds may have double tapers, the more severe taper being in the top section. The mold stool serves as the bottom closure for the mold cavity in all big-end-down molds and in the open-bottom big-end-up molds. The mold itself provides the bottom closure in the closed-bottom big-end-up mold. In the plug-bottom big-end-up mold, the interior is constricted at the bottom to a small, circular opening.
that is closed with a refractory or metal plug prior to casting (see Figure 20–3). Although erosion from impingement of the pouring stream is expected to be confined to the plug in the plug-bottom mold, some erosion of the mold occurs because the plug is too small in diameter to completely protect the bottom. The small opening in the bottom originally was intended to facilitate the use of a plunger to loosen ingots that might stick in the molds, but today most plants do not use a bottom plunger.

The inner walls of molds may be plain sided, cambered, corrugated, or fluted (Figure 20–4). The purpose of corrugating and fluting is to minimize surface cracking of some types of ingots during solidification and cooling by increasing mold-wall area, which has the effect of increasing initial ingot-skin thickness by promoting faster cooling. Corrugated molds are more common than fluted molds. Most corrugations vary from about 13 to 19 mm (0.5 to 0.75 inch) inches high, with distance between centers varying from about 75 to 150 mm (3.0 to 6.0 inches).

In addition to these molds, which are all filled by a stream of liquid steel poured into the mold cavity from above “top-pouring”, “bottom-poured” ingot molds also exist, in which the steel is fed into the bottom of the mold through refractory lined feeders. In the USA, top-pouring is much more widely used, but the use of bottom-pouring is increasing, especially for high-quality steels.

There is a close relationship between ingot shape and slabbing mill yield. Thus, for ingot weights below 3½ tons, the best yields are achieved with closed-bottom semi-circular or near semi-circular designs. For ingots over 3½ tons produced in closed-bottom molds
and also for open-end molds, the optimum bottom design is a full volume pyramid possessing a volume less than 2 per cent, a depth of about 2½ inches and an angle of about 25 degrees. For top quality products, ingots with this cross sectional geometry will yield bottom-end losses of less than 2½ per cent.

Types of Steel—As the mold is being filled with molten steel, the metal next to the mold walls and mold stool is chilled by contact with the cold surfaces and solidifies in these regions to form an ingot shell or ingot skin. Early during solidification, the ingot skin contracts as it cools and forms an air gap between itself and the mold wall; this gap reduces the rate at which heat can be transferred from the steel to the mold and thence to the atmosphere. Also, as solidification proceeds, the thermal gradients become less steep. The thickness of the ingot skin (frozen zone) increases rapidly at first but slows down greatly as solidification proceeds.

The solubility of gases in molten steel decreases with decreasing temperatures, especially when the steel changes from the liquid phase to the solid phase. During the solidification of ingots, the gases are liberated in amounts dependent upon the amount of gases originally present in the molten steel. Oxygen is the chief gas that is involved. It reacts with carbon in the steel and produces carbon monoxide that is evolved from the steel. The addition of deoxidizing agents to the liquid steel decreases the amount of dissolved oxygen, and the degree of deoxidation establishes four types of steel—killed, semikilled, capped, and rimmed—to be discussed later.

Time for Solidification of Ingot—The rate at which heat is extracted from an ingot and, hence, the rate of solidification, is affected by many factors, some of which are the thickness, shape, and temperature of the mold; the amount of superheat of the the liquid steel; the cross-section of the ingot; the type of steel; and the chemical composition of the steel. Figure 20—5 shows the idealized solidification pattern of a 813-mm by 813-mm (32-inch by 32-inch) killed-steel ingot. The lines marked 20, 40, 60, etc., indicate the progress of ingot solidification for the corresponding number of minutes that had elapsed after pouring. The location of these lines was established on the basis of data obtained by casting a series of identical ingots and then dumping each ingot after progressive predetermined intervals to pour out the remaining liquid steel. The solidified shells were then removed from the molds and split vertically for examination and study. The ingots used in the experiment had the following chemical composition:
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Element    Per Cent
C          0.83
Mn         0.77
P          0.014
S          0.024
Si         0.18
Ni         2.08
Cr         0.15

Recent work in Japan (1980) has shown the feasibility of rolling ingots that have not completely solidified during soaking. Interestingly, such a practice results in improved homogeneity of the workpieces as well as large reductions in the fuel used by the soaking pits.

The relationships for determining the comparative rates of ingot solidification for various sizes and shapes are complex and outside the scope of this book.

Range of Ingot Sizes—Ingots may range in weight from well over 270 metric tons (300 net tons) each for large forging ingots to only a few hundred kilograms (several hundred pounds) each for specialty-steel ingots (e.g., tool-steel ingots). Slab ingots range in weight from 9 to 30 metric tons (10 to 40 net tons), with many of them in the neighborhood of 18 metric tons (20 net tons) each. Ingot shape and weight are selected to meet the requirements of the product to be made and the rolling or other equipment that is to be used for hot working.

INTERNAL STRUCTURE OF INGOTS

Introduction to Types of Ingot Structure—When molten steel cools to the temperature range in which it begins to solidify, the solubility of gases dissolved in the steel decreases and the excess gases are expelled from the metal. Of greater importance, the chemical equilibrium between carbon and oxygen changes with decreasing temperatures, so that the two elements react to form carbon monoxide that is evolved as the system attempts to attain a new equilibrium. Molten steel does not solidify at one definite temperature but over a temperature range, so that the gases evolved from still-liquid portions may be trapped at solid-liquid interfaces of the remaining liquid with previously solidified metal to produce blowholes.

The amount of gases, chiefly oxygen, dissolved in liquid steel and the amount of gases released during solidification determine the types of ingots: killed, semikilled, capped, and rimmed. The amount of oxygen dissolved in molten steel is dependent upon the carbon content of the steel, upon the type and amount of deoxidizers added to the steel, and the chemical composition of the steel.

Figure 20—6 illustrates diagrammatically eight typical conditions of commercial ingots, cast in identical bottle-top molds, in relation to the degree of suppression of gas evolution. The dotted line indicates the height to which the steel originally was poured in each ingot mold. The ingot structures range from that of a fully-killed or dead-killed ingot (No. 1) to that of a violently rimming ingot (No. 8). The differences between these structures are the result of the differences in the amount of gas evolved by these ingots as they solidified.

The fully-killed ingot (No. 1) evolved no gas, its top was slightly concave, and directly below the top was an intermittently-bridged shrinkage cavity that is commonly called pipe. While fully killed steels are commonly poured in big-end-up molds that have refractory-type hot tops so as to confine the pipe cavity entirely to the hot-top portion that is later discarded, ingot No. 1 has been included here for comparative purposes. When fully-killed steels are poured in big-end-down, open-top molds, refractory sideboards (insulating or exothermic) are commonly used as replacements for hot tops. Normally, mold additions of deoxidizers are not made to produce killed steel.

A typical semikilled ingot is shown as ingot No. 2. In this ingot, only a slight amount of carbon monoxide was evolved; however, the resulting blowholes developed slowly but were sufficient in volume to compensate fully for the shrinkage encountered during solidification. Ferrostatic pressure (hydraulic pressure exerted by liquid steel due to gravity) prevented the formation of blowholes in the lower half of the ingot. The pressure caused by the trapped gases in the blowholes was sufficient to bulge the surface of the ingot to produce a domed top.

Ingot No. 3 evolved more gas than ingot No. 2 during solidification. The resulting blowholes had a greater volume than that required to compensate for shrinkage resulting from solidification. Some of the blowholes formed very close to the side surface in the top half of the ingot. Blowholes are undesirable so close to the ingot surface since they may result in surface defects (seams) upon subsequent heating and rolling, as dis-
cussed later under "Blowholes." Also, the gas pressure ruptured the initially frozen top surface of the ingot and forced liquid steel up through the rupture where it froze; this phenomenon is called bleeding. Excessive bleeding causes pipe cavities or spongy surface on product rolled from such an ingot.

Ingot No. 4 evolved so much gas that the top ingot surface could not solidify immediately after pouring. Instead, numerous honeycomb blowholes formed very close to the side surface of the ingot, extending from top to bottom. The evolution of gas caused the steel to rise after pouring and produced a boiling action that is commonly called rimming action. This action was stopped by a metal cap secured to the top of the mold.

Ingot No. 5 represents a typical capped ingot. It evolved so much gas that the resulting strong upward currents along the sides in the upper half of the ingot swept away the gas bubbles that otherwise would have formed blowholes. Even in the lower half of the ingot, the blowholes could not form until the gas evolution had moderated somewhat. The result was that a thick solid skin formed first that was then followed by the zone containing the honeycomb blowholes. An ingot of this type would not have the interiors of its blowholes exposed to oxidation by sealing of the ingot surface during heating and soaking. Because this ingot No. 5 had fewer blowholes than did ingot No. 4, the steel rose less rapidly to the cap at the top of the mold.

Ingot No. 6 is a rimmed ingot, as are also ingots No. 7 and No. 8. In ingot No. 6, the evolution of gas, while greater than in ingot No. 5, was insufficient to prevent the honeycomb blowholes from exceeding in volume the amount required to offset solidification shrinkage. Therefore, the top surface of the ingot rose slightly as it froze in from the sides of the mold.

Ingot No. 7 represents a typical rimmed ingot in which gas evolution was so strong that the formation of blowholes was confined to only the lower quarter of the ingot. The apparent increase in volume due to blow holes offset the shrinkage that occurred during solidification. As a result, the top of the ingot did not rise or fall appreciably during solidification.

Ingot No. 8 illustrates a violently rimming ingot, typical of low-metalloid steel. Honeycomb blowholes could not form and the top surface of the ingot fell markedly during solidification.

The foregoing eight ingot structures were selected merely to illustrate a series of cast structures ranging from a fully killed steel to a fully rimmed steel. Included in the series were the four main types of ingots that are produced commercially: killed steel (No. 1), semi-killed steel (No. 2), capped steel (No. 8), and rimmed steel (No. 7).

As was mentioned earlier, oxygen is the principal gas dissolved in steel that makes it possible to produce the various types of ingots. It reacts as follows with carbon during cooling and solidification:

$$O + C = CO \text{ (gas).}$$

The reaction to the right of the equation may be explained as follows: at the tapping temperature, the oxygen and carbon contents of the liquid steel are essentially in equilibrium; however, as the metal cools, the equilibrium is changed and the reaction proceeds toward the right of the equation in an attempt to restore the chemical balance of the system. Because cooling in the mold is continuous, a new state of equilibrium is not attained, and gases continue to be evolved.

The last gases to be evolved may not be able to rise in the ingot, and may collect as bubbles to form blowholes.

**Blowhole Formation**—The mechanism of formation of primary blowholes is illustrated in Figures 20—7, 20—8 and 20—9. In Figure 20—7, bubbles of gas first form at the solid-liquid interface (a) because of the decrease in steel temperature. If the gas evolution is fast and if the liquid is moving upward rapidly along the interface, the bubbles are swept away. If the gas evolution is slow and if the liquid is not moving rapidly, the bubbles will grow as solidification proceeds, as indicated in (b) and (c). Figure 20—8 illustrates that, if the bubbles grow slightly faster than the advancing solidification front, the protruding bubble will break off periodically as shown in (d), (e), and (g). Figure 20—9 shows that, if the bubble growth is accompanied by upward motion of liquid, the bubble will be swept away carrying some of the gas surrounded by solid steel as shown in (d1), (e1), (f2) and (g1). In a properly rimmed ingot, the rapidly moving metal sweeps the bubbles from the solid interface and no primary blowholes are formed in the top portion of the ingot and during the early stages of solidification. But in the bottom of the ingot, the action of the liquid is less pronounced, and the ferrostatic head suppresses the liberation of the gases, so that primary blowholes are formed. The primary blowholes will continue to grow but at a slower rate because there is less oxygen available in the steel until there is enough pressure resulting from the ingot top freezing or capping to suppress the release of gases temporarily. As solidification continues, there is enough oxygen remaining in the liquid to cause an evolution of gas despite the high internal pressure in the ingot; hence spherical secondary blowholes form. The internal pressure is decreased somewhat by the cooling of the steel.

Since the amount of oxygen dissolved in liquid steel decreases with increasing carbon content (excluding the effect of deoxidizers), it becomes apparent that rimmed or capped ingots, that require the evolution of large amounts of gas, cannot be produced if too much carbon is present. The practical upper limit of carbon content for such steels is 0.30 per cent. Killed and semikilled ingots can be produced in steels of low carbon and high oxygen contents by adding deoxidizers to the liquid steel to react with and remove the oxygen. However, in such low-carbon steels, the required large amounts of deoxidizers to be added not only would add to the cost of the steel, but also may produce an excessive number of nonmetallic inclusions representing the products of the deoxidation reactions. Therefore, there are often practical advantages in producing the lower carbon steels by rimmed or capped practice, and the higher carbon steels by semikilled or killed practice.

In all except killed-steel ingots, the evolution of gas produces cavities of roughly cylindrical shape (skin or honeycomb blowholes) or of spherical shape (located deeper in the ingot). Except for the ones located within several inches of the top of the ingot, such blowholes
Pipe—The shrinkage cavity, or pipe, located in the upper central portion of the ingot, is largest and most deeply located in the two extremes of ingot structure represented by ingots Nos. 1 and 3 in Figure 20—6. Less extreme structures such as No. 2 (semikilled) or No. 7 (strongly rimming) exhibit this tendency to a lesser extent, while the product of an ingot of intermediate structure such as No. 5 (capped) will be practically free from pipe after rolling. Big-end-down killed ingots (poured without a hot top) often have the lower, unoxidized portion of the pipe cavity below the bridges clean enough to be welded completely shut by pressure and deformation of the steel during rolling. This is particularly true for steels of higher carbon content or for steels that are extensively reduced during rolling, as in the lighter-gage flat-rolled products. A satisfactory yield of sound rolled product often can be obtained with such steels without taking special steps to prevent the formation of pipe.

If assurance of complete freedom from pipe is required, it is accomplished best in killed-steel ingots by making them big-end-up with a hot top, as shown in Figure 20—10 (No. 1). This figure also illustrates the extent of pipe in hot-topped and non-hot-topped ingots of the big-end-down and big-end-up types. The refractory material with which the hot top is constructed or lined absorbs heat less rapidly than the cast iron of the mold, so that the top of the ingot remains molten until after the remainder of the ingot has solidified, thus furnishing an overlying pool of liquid steel that feeds down into the portions of the ingot below the hot top to overcome the shrinkage due to solidification. By using big-end-up molds, this feeding is made still more effective.

To improve the feeding of metal by hot tops, especially during the late stages of solidification, efforts are directed toward keeping the metal pool in hot tops liquid as long as possible. Several methods are used to do this. One method is to use a highly insulating refractory material in the hot top. Another method is to use exothermic materials as part of the hot top and as a covering over the top of the steel. When killed steels tend to have interiors free of an oxide coating and clean enough to weld easily and completely during rolling. However, if the blowholes extend to the surface of an ingot, or lie at such shallow depth beneath the surface as to become exposed by scaling of the ingot surface during heating in the soaking pits, they can become oxidized and will not weld; instead, they may produce numerous seams (sometimes termed brush seams) in the rolled product. Properly made ingots, therefore, will have gas evolution during solidification so controlled that there will be a skin of adequate thickness over those blowholes closest to the surface. The fact that blowholes serve a useful purpose in diminishing or preventing the formation of pipe and improving ingot yield already has been mentioned.
are poured in big-end-down ingot molds, the more common practice is to use insulating or exothermic sideboards. Still another method is to employ an electric arc to provide heat to the top of a non-hot-topped ingot.

Segregation—The amount of segregation found in an ingot depends upon several factors, some of which are the chemical composition of the steel, the type of ingot (killed, semikilled, capped, or rimmed), and the ingot size. A detailed explanation of segregation, dendrite crystal formation, and solidification rates of ingots is outside the scope of this discussion. In general, the metal that solidifies very rapidly close to the mold wall (the chill zone) has about the same chemical composition as the liquid metal entering the mold. However, as the rate of solidification decreases, the mechanism of solidification is such that dendrite crystals of purer metal solidify first; that is to say, the first crystals to form contain less carbon, manganese, phosphorus, sulphur, and other elements than the liquid steel from which they formed, and the remaining liquid is enriched by these elements that are continually being rejected in the crystallization process. Thus, the last material to solidify contains the largest amount in total of the rejected elements. Segregation is frequently expressed as a departure from the average chemical composition. Thus, when the content of an element is greater than the average, the segregation is termed positive segregation; when the content is less than the average, it is termed negative segregation.

Some elements in steel tend to segregate more readily than others. Sulphur segregates to the greatest extent. The following elements also segregate, but to a lesser degree, and in descending order: phosphorus, carbon, silicon, and manganese. The tendency for elements to segregate while an ingot is solidifying increases with increased time for solidification, so that large ingots exhibit more severe segregation than do small ingots.

Also, when comparing ingots of the same cross-section, movement of liquid steel by convection currents or turbulence due to gas evolution in the steel in a mold during solidification increases the tendency of elements to segregate. Therefore, killed steels are less segregated than semikilled; the semikilled less segregated than capped or rimmed steels. In a rimmed ingot, the rimmed zone exhibits negative segregation and the core zone exhibits positive segregation. The boundary between the rim and core zones of a rimmed ingot is very sharp and these zones are so different with respect to chemical composition that they resemble different steels.

There are certain other special aspects of segregation in killed steel that are of interest, but can only be mentioned here; these include axial porosity (associated with the "V" segregate" along the central axis of an ingot) and ingot pattern that may be due to the ingot being disturbed while solidifying, or to the type of segregation referred to as "inverted V" segregate." Alternatively, these are known as "A' segregates."

Columnar Structure—Steel after solidification is a crystalline material. The first molten metal to contact the comparatively cold mold wall freezes (solidifies) rapidly, with a structure characterized by small and randomly oriented crystals that form a chill zone about 12 mm (½ inch) thick. After this initial zone of randomly oriented crystals has formed, large crystals (dendrites) that are characterized by a branching structure develop. Growth of the individual dendrites occurs principally along their longitudinal axes perpendicular to the surfaces of the ingot, and these large elongated crystals may extend all the way to the center of the ingot. An ingot possessing a preponderance of these large elongated crystals is referred to as having a columnar structure and, if the structure is exaggerated in extent, it is referred to as ingotism. Ingots exhibiting ingotism tend to crack excessively during rolling unless light drafts (small reductions in cross-sectional area per pass) are employed for the first few passes in the rolling mill. In most ingots, however, columnar structure gives way, toward the center of the ingot, to rather large, equiaxed, randomly-oriented crystals that also are dendritic in character. The relative proportion of columnar and equiaxed dendritic crystallization appears to be dependent upon many variables, among which are: composition of the steel, mold temperature, pouring temperature, and gas content of the steel.

Methods for moving the liquid steel in a mold during the initial time of solidification by various mechanisms such as pneumatic oscillation have been successful in decreasing and sometimes eliminating the zone of columnar crystals but such practices are the exception rather than the rule.

The success of these mechanisms in minimizing and sometimes eliminating the formation of columnar crystals can be explained as follows:

Essentially, all such induced movements of the liquid steel ingot core must achieve two objectives if columnar growth is to be terminated and equiaxed growth achieved. These two objectives are (1) the removal of all superheat in the liquid core (superheat is defined as the temperature of the liquid above its liquidus temperature.) Thus, the removal of all superheat means the liquid core will be at the liquidus temperature of the steel; and (2) the generation of nuclei fragments in the liquid core, either by mechanically breaking or remelting the columnar dendrite tips.

Long columnar crystals, especially in higher alloy grades that tend to resist plastic flow at hot-rolling temperatures, are undesirable because of their poor cohesive strength which causes the steel to rupture along the periphery of the columnar crystals during the hot-forming operation.

Internal Fissures—Tensile stresses in the interior of an ingot, arising during heating, cooling, or rolling, may produce internal fissures or internal bursts, sometimes of a very large size. If these do not extend to the surface, they may weld completely during the rolling operation, provided that the amount of hot work (percentage of reduction) is sufficient.

Ingot Cracks—These defects occur as both transverse and longitudinal ruptures in the ingot wall, and normally are observed first while the ingot is being rolled on the primary mill, although some are apparent on the surface of the ingot itself, especially if it becomes cold. Ingot cracking has been the subject of numerous investigations, and some of the causes have
been brought to light, although many still remain obscure. Excessively high pouring temperature (a temperature considerably above the solidification temperature) has been established as one definite cause of ingot cracking. During solidification, a dendrite crystalline structure is developed in the ingot and interdendritic zones of weakness are formed which extend from the ingot surface toward the center. The larger the dendrites, the more pronounced are these zones. Lower pouring temperatures will help eliminate cracking from this origin by limiting the size while increasing the total number of individual dendrites. Fields due to surging of the molten metal in the mold form discontinuities in the ingot wall that lead to transverse ingot cracking. This type of defect has been minimized by use of mold coatings and improved mold design. Steels of the 0.15 to 0.25 per cent carbon grades, especially the fine-grained killed types, have the greatest tendency toward transverse cracking. Generally, the higher carbon steels have the least tendency toward this transverse rupturing. Hanging of hot-topped ingots by fins forming over the edge of the mold wall usually produces a transverse crack approximately 150 mm (6 inches) below the hot-top junction, easily recognizable and termed a hanger crack. Hanger cracks from this source can be prevented by use of properly designed hot-tops. Plain-sided molds are more prone to produce or at least accentuate transverse cracking than the fluted type. Longitudinal cracks generally are related to the flute or corner design of the mold.

Other and more obscure causes and corrective measures for ingot cracking are a constant subject for study by practically all steel-mill personnel.

Nonmetallic Inclusions—All steel ingots contain nonmetallic inclusions that consist of oxidized material and lesser amounts of sulphides in various combinations and mixtures with each other. They are derived chiefly from the oxidizing reactions of the refining processes and the deoxidizing materials added to the steel in the furnace, ladle, or molds. Some may result from erosion of ladle and other refractories during pouring or chemical action of these refractories with the steels.

Seabs—In top-poured ingots, the pouring stream first strikes the stool or the mold bottom, and splashes violently against the lower part of the mold walls. Many of these splashes adhere and solidify, forming a continuous layer on the lower portion of the mold walls. This splashing diminishes as a pool of liquid metal forms in the bottom of the mold. The adhering splashes cool rapidly, and their surfaces oxidize. If the cooling and oxidation have progressed too far by the time the liquid steel in the mold rises past them, they will not be incorporated into the ingot, but will remain as adhering and imperfectly bonded seas on the surfaces of the ingot. If thin, seas may be oxidized away by scale formation in the soaking pit. If thick, they remain and produce a similar defect on the rolled product. As the continuous layer of splashes cools, its upper edges tend to bend inward and, as the rising liquid steel overflows them, to become enfolded. Horizontal ingot cracks called butt cracks often occur below and parallel to such folds, and the folds themselves can produce surface laminations or seams in rolled product.

The defects associated with pouring splashes can be reduced by filling the mold more rapidly, so that the rising level of liquid steel covers the splashes before they can cool and oxidize. This is done by using larger or multiple nozzles, which practice, however, leads to various mechanical difficulties if carried to extremes. Some steel plants use metal "boots" or stovepipe type sheet-metal cylinders set on end on the stool to contain the initial splash; after the pouring stream is opened full, these rapidly melt into the liquid metal. Bottom pouring also will minimize these defects, since the molten steel enters the mold from a runner through an opening in the mold bottom and there is little splashing as compared with top-pouring practice.

Mold Coatings—Another method of reducing the effects of splashing, and thereby improving the surface of ingots, is to coat the inside of the molds with a substance that will volatilize and tend to repel splashes. Some coatings such as tar and powdered pitch are effective as splash repellents but are no longer being used because of environmental and health hazards. Mold temperatures are important in applying mold coatings. If they are too hot, the coating will not adhere to the mold walls and, if the coating materials are carbonaceous, they will decompose and the resulting residual charred film has no beneficial effect. If they are too cold, the coatings are extremely heavy, and the excessive evolution of gases when in contact with the liquid steel gives rise to subsurface pinholes and blowholes in the ingot surface. Refractory-base mold coatings are also used to a limited extent.

Practices have been developed to eliminate mold coatings by using, instead, clean molds and optimum pouring rates that minimize surface imperfections.

PRODUCTION OF DIFFERENT INGOT TYPES

The foregoing discussion has shown that the final structure of an ingot is determined almost entirely by the degree to which the steel from which it was cast has been deoxidized. The several types of steel require different steelmaking and deoxidation practices, which are described briefly in the following summary of the principal steps involved.

Rimmed Steels—For rimmed steels, proper rimming action in the molds has been described as necessary to produce the surface conditions and ingot structure desired. Slag control is aimed at adjusting the lime-silica ratio and iron-oxide content of the slag to give the desired level of oxidation of the bath of metal when the heat is ready to tap. The exact procedures followed depend upon whether the steel has a carbon content in the higher ranges (0.12 to 0.15 per cent), in the lower ranges (0.06 to 0.10 per cent), or under 0.06 per cent.

Rimmed steel usually is tapped without additions of deoxidizers to the steel in the furnace, and with only small additions to the molten steel in the ladle, in order to have sufficient oxygen present to give the desired gas evolution by reacting in the mold with carbon. Ferromanganese may be added to the furnace before tapping in open-hearth or electric-furnace operations, or to the ladle, but it is usual to make the addition in the ladle. Aluminum, ferrotitanium, or other deoxidizers in small amounts may be added in the ladle, if needed. This type of steel, when properly made, can be cast
into ingots having a minimum of pipe and a good surface, though they are subject to segregation. When the metal in the ingot mold begins to solidify, there is a brisk evolution of gas, resulting in an outer ingot skin of relatively clean metal. For many applications, particularly where the surface of the product is most important, this steel is used to a considerable extent.

The thickness of the outer skin and the absence of blowholes and oxides within it depend upon the skill of the steelmakers. When the temperature and the oxygen content of the steel as it is poured from the ladle are within the most desirable limits, the desired evolution of carbon monoxide from the steel in the molds is obtained. The rimming action of the first-cast ingot is observed, and if an increase or decrease in the rimming action is desired, this is obtained for subsequent ingots by making small adjustments in the amount of shot aluminum or gas-evolving materials depending upon whether the oxygen level is, respectively, too high or too low. If the steel is over-deoxidized (oxygen content too low), the rimming action will be incomplete because gas evolution is too small in volume and slow in starting. The use of hot molds will also suppress rimming action. If the steel is too high in oxygen content, there is an absence of blowholes, the level of liquid steel falls and the incidence of pipe increases.

Capped Steels—Capped-steel practice is a variation of rimmed-steel practice. The steel is poured into big-end-down bottle-top molds in which the constricted top or mouth of the mold facilitates the capping operation. The rimming action is allowed to begin normally, but is then terminated at the end of a minute or more by sealing the mold with a cast-iron cap. The addition of only a small amount of shot aluminum during pouring insures that the steel will rise to press against the cap. The oxygen level of the steel as poured into the mold is preferred to be not more, and possibly slightly less, than the level desired for rimmed steel. The capped ingot has a thin rim zone that is relatively free from blowholes, and a core zone that has less segregation than that for a rimmed-steel ingot of the same volume. In steels with a carbon content greater than 0.15 per cent, the capped-ingot practice is used with advantage. Steels of this type are applied to sheet, strip, skelp, tin plate, wire, and bars. Ingots are also "splash capped." For this practice, a rimming type of steel is poured into bottle-top molds just into the shoulder section of the molds, is allowed to rim for a predetermined period of time ranging from a few to several minutes, then the mold is filled into the neck section and immediately capped.

Semikilled Steel—Semikilled steel is deoxidized less than killed steel, and there is enough oxygen present in the molten steel to react with carbon and form gas after the steel is poured into molds. Semikilled steel finds wide application in structural shapes, plates, and bar products. This steel generally has a carbon content within the range of 0.15 to 0.30 per cent. The usual practice is to bring the carbon content of the steel in the furnace to the desired carbon content for tapping. Ferromanganese may be added to the furnace in the case of an open-hearth or electric furnace, to the ladle, or to both. Carbon, ferrosilicon, and aluminum may be added to the ladle. Usually, most deoxidation is done in the ladle, so that only a few grams (ounces) of aluminum per ton of steel will be required as a mold addition to produce the desired level of deoxidation so that gas bubbles are trapped in the upper portion of the ingot during solidification.

Killed Steel—The term "killed" indicates that steel has been deoxidized sufficiently for it to lie perfectly quiet when poured into an ingot mold. There is no evolution of gas in the mold, and the top surface of the ingot solidifies with relative rapidity. Killed steel generally is used when a homogeneous structure is required in the finished steel. Alloy steels, forging steels, and steels for carburizing are of this type, when the essential quality is soundness. In general, all steels with more than 0.30 per cent carbon content are killed.

In making killed steel in the open-hearth, the usual steelmaking-furnace practice is to "catch the heat coming down," that is, to decrease the carbon content of the bath to the desired level and then either to block the heat (deoxidize it) by adding high-silicon pig iron (15 to 25 per cent silicon), 50 per cent ferrosilicon, or silico-manganese, or to tap the heat without blocking and depend upon ladle deoxidation. Blocking lowers the oxygen content of the liquid metal to prevent further oxidation of carbon; it also serves to protect alloying elements that are susceptible to oxidation and, consequently, are added after the heat has been blocked.

At the final part of the finishing period, the carbon will have been worked down until it is at a level within the range required for tapping and pouring. The phosphorus and sulphur contents should be below the specified maximum, the manganese usually will be below the minimum required, and the bath temperature should be proper for the composition and grade of the steel being produced. The steel is then ready for whatever ferroalloys need to be added.

The decision as to whether a ferroalloy addition is to be made to the furnace or to the ladle is determined largely by the susceptibility of the ferroalloy to oxidation. Manganese may be added to the furnace or to the ladle, or divided between them, but the additions to the ladle must not be so large as to chill the metal too much. The furnace additions are chosen and the timing of addition set so that maximum elimination of the solid oxides formed will take place by their floating up through the metal to the slag before the metal is tapped from the furnace. After tapping, other deoxidizing additions may be made to the steel as it runs into the ladle. These additions complete the deoxidation to the desired degree up to the pouring into molds. These ladle additions are usually ferrosilicon, aluminum, or some special alloys (calcium-silicon is an example) containing elements that have a strong affinity for oxygen. Additions containing such elements as manganese and silicon furnish part of these elements required to meet the chemical-composition specifications. Additions of deoxidizers may be made to the molds, depending upon the type of steel; however, this is rarely practiced except by some plants which may add aluminum to the last three or four ingots to make up for any possible loss to the oxidizing slag floating on the metal in the ladle.

For the pneumatic (BOP, Q-BOP) processes, the common practice is also to "catch the heat coming down" in carbon content, and if the heat is at the de-
PRODUCTION OF SEMI-FINISHED STEEL BY INCOT CASTING AND ROLLING

sized carbon, phosphorus, sulphur and temperature levels at turndown, the heat is tapped into a ladle where almost all additions are made during tapping and only small additions are sometimes made in the molds during teeming. Tapping temperatures are adjusted upward as the amount of ladle additions (except for silicon) are increased. When temperature losses are excessive, exothermic materials are used as ladle additions.

In some BOP shops, the heats are blown to low carbon contents (less than 0.10 per cent), tapped, and ladle-refined where the steel is recarburized to high-carbon contents (more than 0.30 per cent).

Most killed steels are cast in hot-topped big-end-up molds. However, for economic reasons, some killed steels are cast in big-end-down molds with either insulating or exothermic sideboards.

SECTION 2

ROLLING OF BLOOMS, SLABS AND BILLETS

Introductory—There is no widely accepted precise definition for the terms bloom, slab, or billet, and local applications of the terms are used somewhat on a traditional basis. Distinctions are made according to general appearance, influenced by overall size and the proportions of the three linear dimensions and also by intended use. The distinction between blooms and billets is principally a distinction of size, billets being smaller than blooms in cross-sectional area, and both having a length several times greater than their maximum cross-sectional dimension. The distinction between blooms and slabs is principally one of cross-sectional dimensional proportion, blooms tending to be square, or nearly square, and slabs being always oblong and tending to be relatively wide, thin, and (until recently) of short length. There are many exceptions, and there are special names for pieces intended for special uses.

For example, any piece to be rolled into a plate is called a slab, regardless of size or of dimension proportion. Likewise, any piece produced on a billet mill is termed a billet, regardless of shape and size, with the exception of round billets, such as tube rounds. Blooms in short lengths are sometimes called blanks or blocks, and special-shape blooms for structural sections frequently are called blanks regardless of length.

A crude guide using only the cross-sectional characteristics as the distinguishing features which may serve in place of definitions is shown schematically in Figure 20—11.

Until recently, steel in the form of blooms, slabs and billets was produced chiefly by hot rolling ingots to produce blooms and slabs. In this section we first discuss the primary mills used for hot rolling ingots. Following this is a discussion of blooming and slabbing mills. General features of roll pass design are discussed, followed by a discussion of billet mills. Some blooms and slabs were (and still are) produced by other means of hot working, such as forging by hammering or pressing. These are discussed briefly in Chapter 22 and covered in more detail in Chapter 29.

Since the first blooming mill was built in Dowlais, Wales in 1866, there has been continual improvement. In the early 1940's, research and development resulted in the perfection of methods for the continuous casting of molten steel directly into the form of slabs and billets, by-passing the ingot stage and the necessity for hot-rolling operations formerly required to produce such products. Another process known as bottom pressure casting is also employed to produce slabs and billets directly from molten steel. These processes are discussed in detail in Chapter 21.

Bloom, slabs and billets may develop a variety of defects arising from heating, rolling and casting that may have to be removed to prevent their affecting the surface quality of finished products made from them. These defects usually are detected and removed from the blooms, slabs and billets after they have cooled to

TYPICAL CROSS-SECTION AND DIMENSIONAL CHARACTERISTICS*

ALWAYS OBLONG
MOSTLY 50 TO 230 mm (2 TO 9 IN.) T H I C K
MOSTLY 610 TO 1520 mm (24 TO 60 IN.) W I D E

BLOOM
MOSTLY IN THE RANGE 150 mm BY 150 mm (6 IN. BY 6 IN.)
TO 300 mm BY 300 mm (12 IN. BY 12 IN.)

SLAB

BILLET
MOSTLY SQUARE
MOSTLY IN THE RANGE 50 mm BY 50 mm (2 IN. BY 2 IN.)
TO 125 mm BY 125 mm (5 IN. BY 5 IN.)

* DIMENSIONS USUALLY GIVEN TO NEAREST ROUND NUMBER.
ALL CORNERS ARE ROUNDED, AS SHOWN.

Fig. 20—11. Comparison of the relative shapes and sizes of rolled steel governing nomenclature of blooms, primary and billet mills. (Cast sections produced by continuous or bottom pressure casting methods are similarly designated when of the same general proportions and dimensions as their rolled counterparts.)