

General Introduction to Carbon and Alloy Steels

STEELS constitute the most widely used category of metallic material, primarily because they can be manufactured relatively inexpensively in large quantities to very precise specifications. They also provide a wide range of mechanical properties, from moderate yield strength levels

(200 to 300 MPa, or 30 to 40 ksi) with excellent ductility to yield strengths exceeding 1400 MPa (200 ksi) with fracture toughness levels as high as $110 \text{ MPa}\sqrt{\text{m}}$ ($100 \text{ ksi}\sqrt{\text{in.}}$).

As shown in Table 1, carbon steels—steels containing less than 2% total alloying elements—are by far the most frequently used steel (more than 90% of the steel shipped in the United States is carbon steel). Alloy steels—steels containing a total alloy content from 2.07% up to approximately 10%—rank second. Tool steels, as well as the more highly alloyed (minimum 11% Cr) stainless steels, are both produced in lower tonnages than are either carbon or alloy steels. Tool steels and stainless steels will not be addressed in this article as these materials are reviewed in previously published Volumes of the *ASM Specialty Handbook* series.

It should be noted that there is widespread inconsistency regarding the use of the terms “alloy steels” and “low-alloy steels.” For the purposes of this Handbook, the terms are synonymous/interchangeable, i.e., they both refer to steels, *exclusive* of tool steels, containing approximately 2 to 10% total alloying content.

This article will review steelmaking practices used to produce carbon and alloy steel products, describe the various systems used to classify carbon and alloy steels, and discuss the effects of alloying elements on the properties and/or characteristics of steels. Although emphasis has been placed on wrought steels, steel castings and powder metallurgy (P/M) products are also briefly described. This article also serves as a roadmap to the other articles in this Volume that provide supplemental or more detailed information on the fabrication characteristics of steels or their performance in various environments/applications.

Steel Processing Technology

Figure 1 represents the steelmaking flowlines for flat (sheet and strip) steel products (the same melting, refining, and casting methods are used to produce other steel products such as structural shapes, bars, rods and wire, and pipe and tube). Liquid iron, commonly referred to as pig iron, is produced in a blast furnace from iron ore, lime-

Table 1 Net shipments of U.S. steel mill products—all grades

Steel products	1992		1991	
	Tons(a)	%	Tons(a)	%
Ingots and steel for castings	215	0.3	244	0.3
Blooms, slabs, billets	2,255	2.7	2,305	2.9
Wire rods	4,511	5.5	4,366	5.5
Structural shapes (≥ 75 mm, or 3 in.)	5,081	6.2	5,245	6.7
Steel piling	454	0.6	430	0.5
Plates (cut lengths)	4,362	5.3	4,275	5.4
Plates (in coils)	2,740	3.3	2,667	3.4
Rails				
Standard (over 27 kg, or 60 lb)	435	0.5	382	0.5
All other	5	0.0	16	0.0
Railroad accessories	122	0.1	89	0.1
Bars				
Hot rolled	5,806	7.1	5,431	6.9
Bar-size light shapes	1,119	1.4	1,157	1.5
Reinforcing	4,781	5.8	4,859	6.2
Cold finished	1,458	1.8	1,341	1.7
Tool steel	64	0.1	51	0.1
Pipe and tubing				
Standard pipe	1,062	1.3	970	1.2
Oil country goods	979	1.2	1,077	1.4
Line	1,110	1.3	1,439	1.8
Mechanical	790	1.0	744	0.9
Pressure	48	0.1	49	0.1
Structural	142	0.2	151	0.2
Pipe for piling	35	0.0	24	0.0
Stainless	32	0.0	34	0.0
Wire-drawn	900	1.1	865	1.1
Black plate	230	0.3	249	0.3
Tin plate	2,715	3.3	2,754	3.5
Tin-free steel	904	1.1	964	1.2
Tin-coated sheets	78	0.1	74	0.1
Sheets				
Hot rolled	13,361	16.2	13,161	16.7
Cold rolled	12,692	15.4	11,532	14.6
Sheets and strip				
Galvanized hot dipped	8,199	10.0	6,910	8.8
Electrolytic	2,390	2.9	2,099	2.7
All other metallic coated	1,348	1.6	1,146	1.5
Electrical	436	0.5	458	0.6
Strip				
Hot rolled	550	0.7	533	0.7
Cold rolled	832	1.0	755	1.0
Total steel mill products	82,241	100.0	78,846	100.0
Carbon	76,625	93.2	73,480	93.2
Stainless	1,514	1.8	1,449	1.8
Alloy (other than stainless)	4,101	5.0	3,917	5.0

(a) Thousands of net tons. Source: American Iron and Steel Institute

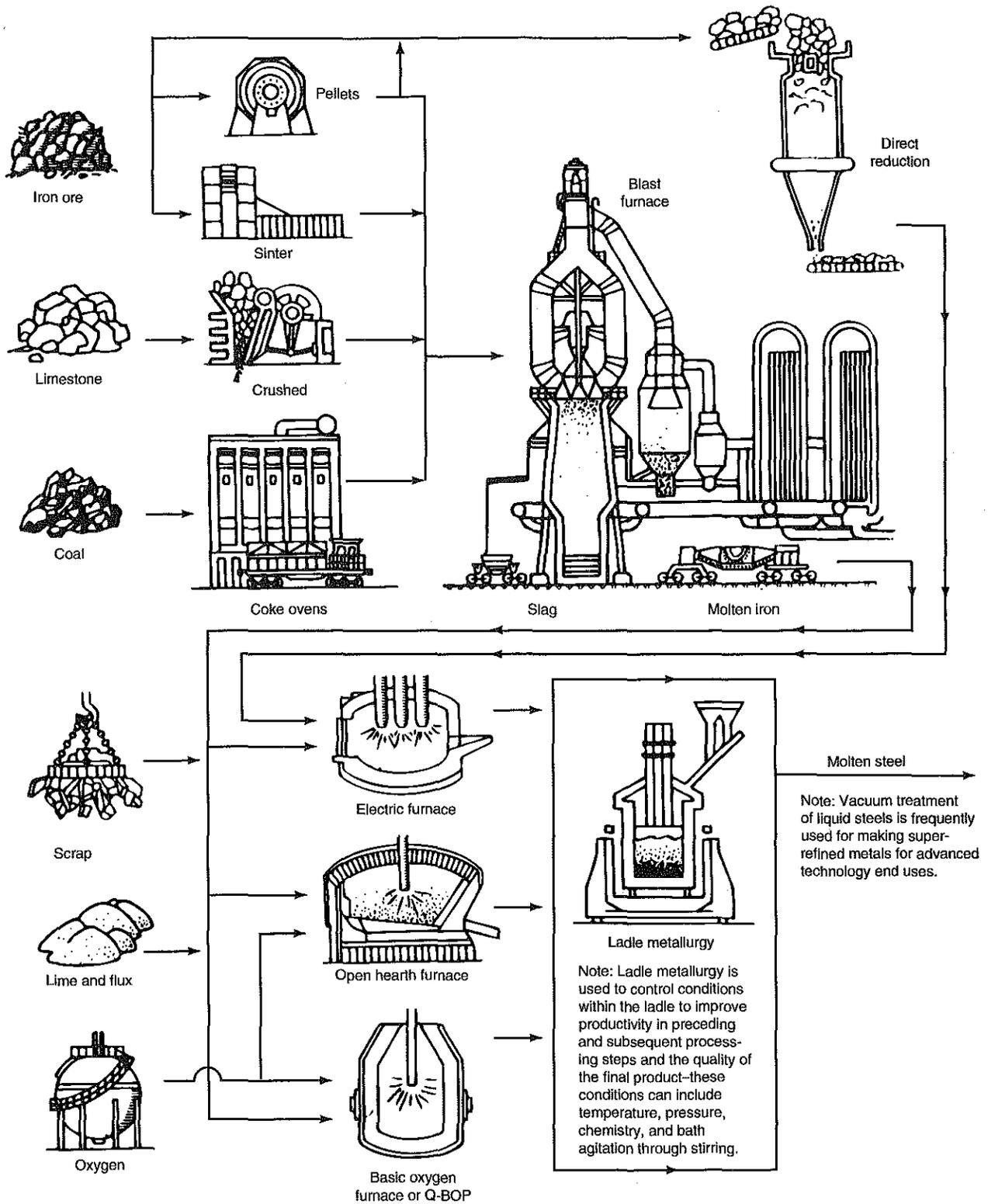


Fig. 1 Flow diagram showing the principal steelmaking steps involved in converting raw materials into flat mill product forms. Source: American Iron and Steel Institute

stone, and coal (coke), but contains excessively high levels of silicon, manganese, carbon, and other elements. This liquid iron, together with scrap and fluxing agents, is then introduced into either a basic oxygen furnace or an electric furnace for further refining with oxygen that reduces

the silicon, manganese, and carbon to acceptably low levels in the resulting steel. The steel is then tapped or poured into refractory-lined ladles. During this tapping operation, alloying elements that will determine the final chemistry of the steel are added to the ladle along with deoxidizing

materials, which have a major influence on the final quality, formability, and cost.

Steelmaking Furnaces and Processes

The most commonly used steelmaking furnaces are the basic oxygen furnace, acid or basic

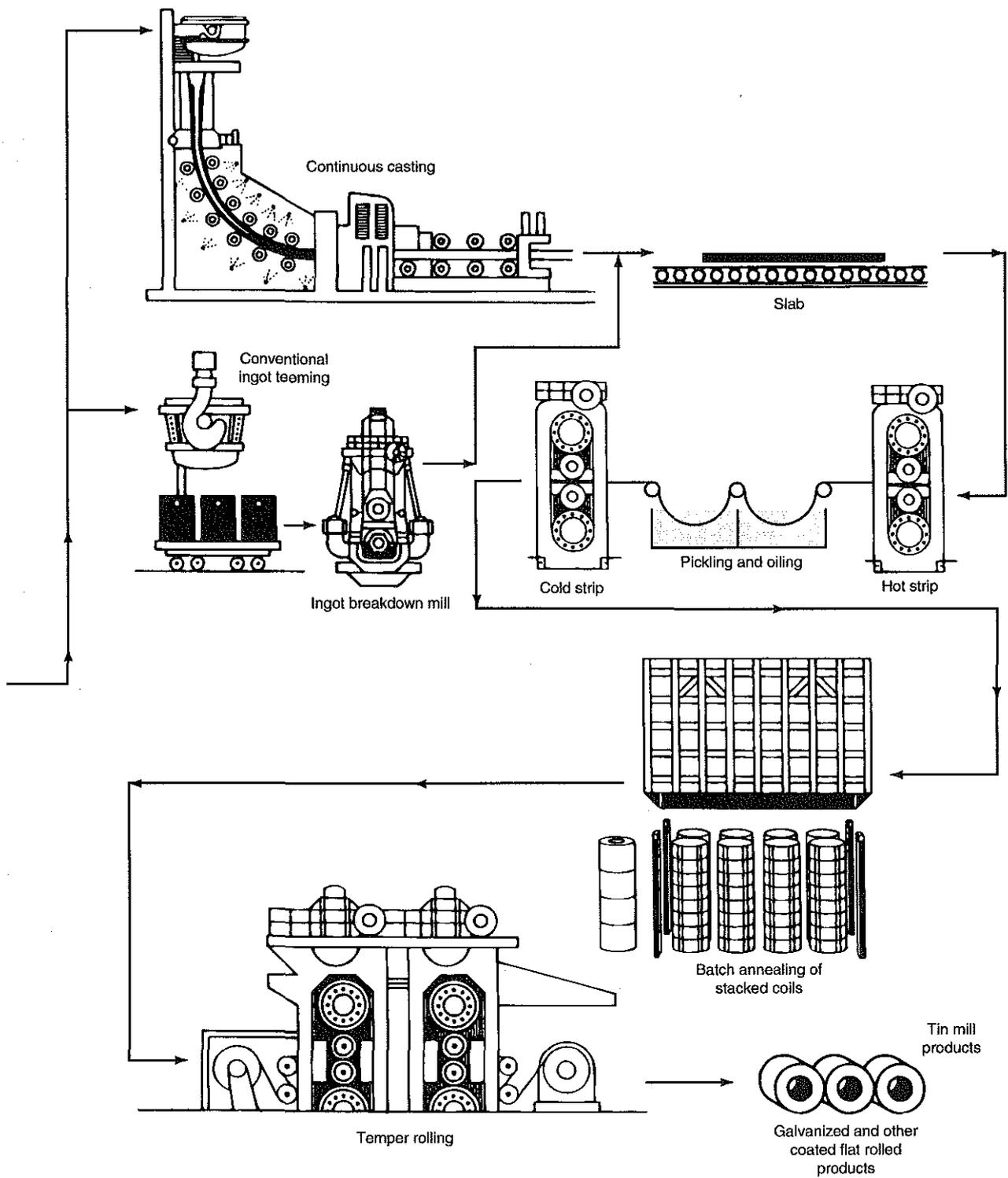


Fig. 1 (continued) Flow diagram showing the principal steelmaking steps involved in converting raw materials into flat mill product forms. Source: American Iron and Steel Institute

electric furnaces, and basic open-hearth furnaces. The distinction between acid and basic is made according to the character of the furnace lining and the flux used in the furnace. A basic furnace is required to reduce the phosphorus content from that of typical pig iron to the maximum amount allowable in most grades of steel.

Historically, the open-hearth process was the principal steelmaking process for high-tonnage

operation. However, the open-hearth process now has been superseded largely by the faster and more efficient basic oxygen process. As a result, it will not be discussed further. Table 2 compares steel production by type of furnace and steel grade.

The Basic Oxygen Process (BOP). A schematic representation of a basic oxygen furnace is shown in Fig. 2. This arrangement consists of a

large tiltable vessel lined with basic refractory material and the necessary accessory equipment. After the furnace is charged with molten pig iron (which usually comprises 65 to 75% of the charge), scrap steel, and fluxes, a lance is brought down near the surface of the molten metal and a jet of high-velocity oxygen impinges upon the metal. The oxygen reacts with carbon and other impurities in the steel to form liquid compounds

Table 2 U.S. raw steel production (in thousands of net tons) by type of furnace and steel grade

See also Table 3.

Year	Open hearth			Basic oxygen process			Electric			Total
	Carbon	Alloy	Total	Carbon	Alloy	Total	Carbon	Alloy	Stainless	
1992	53,745	3,896	57,642	28,713	4,602	1,993	35,308
1991	1,407	2	1,408	48,895	3,819	52,714	27,577	4,319	1,878	33,774
1990	3,209	287	3,496	53,808	4,663	58,471	29,573	5,330	2,037	36,939
1989	4,229	213	4,442	53,677	4,671	58,348	28,325	4,902	1,926	35,154
1988	4,915	203	5,118	52,918	5,042	57,960	28,989	5,657	2,199	36,846

Source: American Iron and Steel Institute

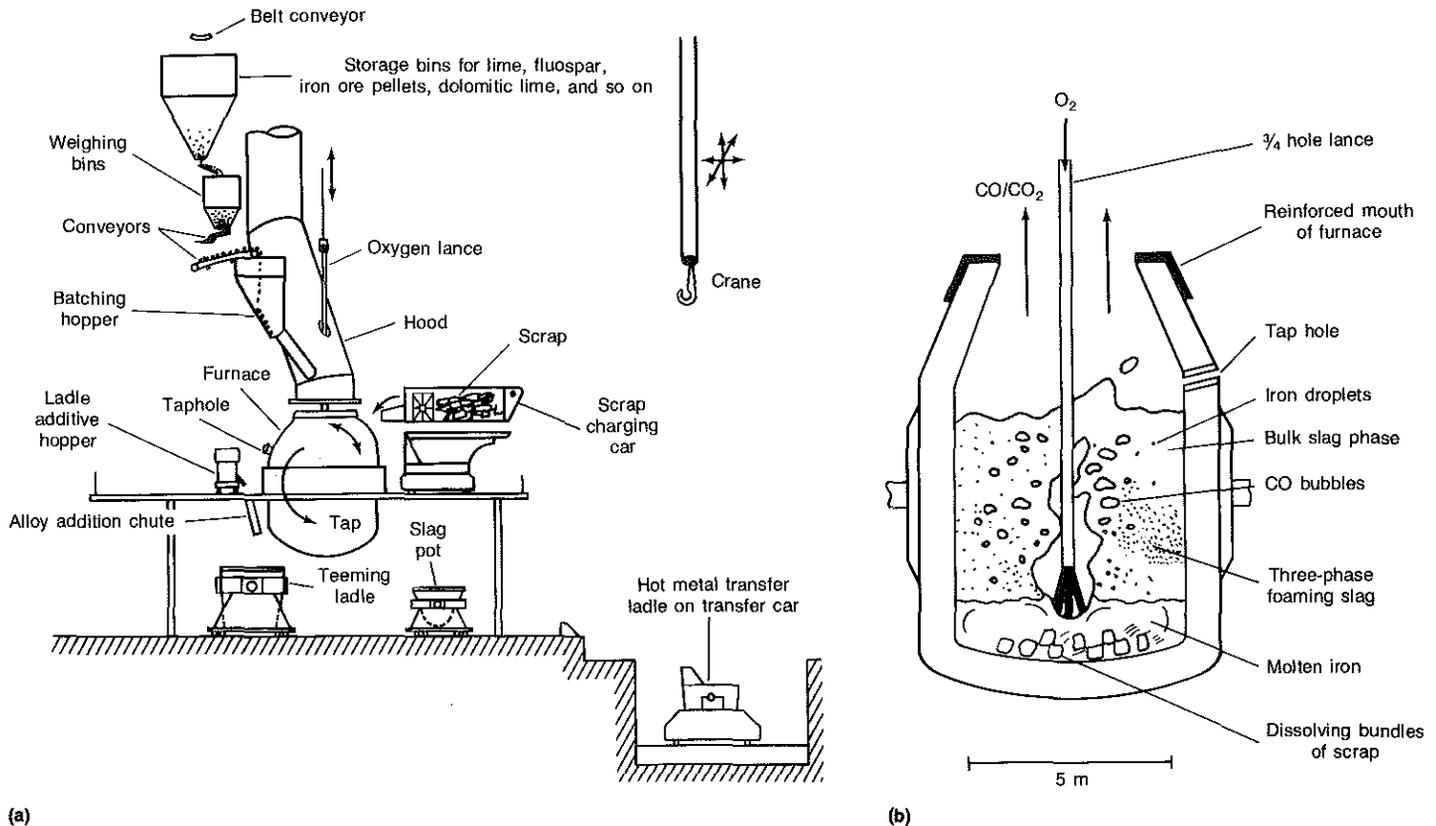


Fig. 2 Principal zones and component parts of a basic oxygen furnace for the production of steel in a melt shop. (a) Typical plant layout. (b) Basic oxygen furnace vessel

that dissolve in the slag and gases that escape from the top of the vessel. A heat of steel can be produced in less than 1 h. No fuel or electric power is required by the basic oxygen furnace (except to operate accessory equipment), but large quantities of oxygen are required. Almost any grade of carbon or low-alloy steel can be made in this type of furnace. Because it uses small amounts of scrap, the amount of tramp alloying elements introduced by the scrap is minimized. Furthermore, some alloying elements, such as chromium, are oxidized preferentially to iron during the oxygen "blow," so that there may be a significant loss of alloying elements during production of alloy steels.

In a bottom-blown basic oxygen furnace, the oxygen is introduced through an opening in the bottom of the furnace, rather than through a

lance. In all other respects, it is similar to the top-blown basic oxygen furnace.

Both types of basic oxygen furnaces require large amounts of molten pig iron; thus, they are normally used in conjunction with blast furnaces in large integrated steel-manufacturing facilities.

The basic oxygen process is now the principal method of high-tonnage steel production.

The Submerged Injection (Q-BOP) Process. The bottom-blown oxygen steelmaking process uses a converter with a replaceable bottom containing tuyeres through which oxygen is introduced. The number of tuyeres depends on the size of the furnace, the number increasing with the size. Tuyere placement is critical if advantage is to be taken of the stirring capability of bottom injection, particularly under conditions where oxygen flow rates are decreased. Replacement of

the bottom refractory plug for the vessel that contains the tuyeres was required four to five times as often as replacement of the remaining vessel lining in the early stages of the process. However, with improved operating and refractory practices, this ratio has been decreased to unity with recent operating practice indicating up to 1000 heats for the bottom plug and working linings of the vessel. The absence of the lance in the bottom-blown process has offered opportunities to decrease total plant height and has also allowed relatively easy conversion of older open-hearth plants.

With the flexibility in plant design and lower conversion costs on a brown-field site, and particularly considering the potential metallurgical advantages, the bottom-blown process has shown rapid adoption.

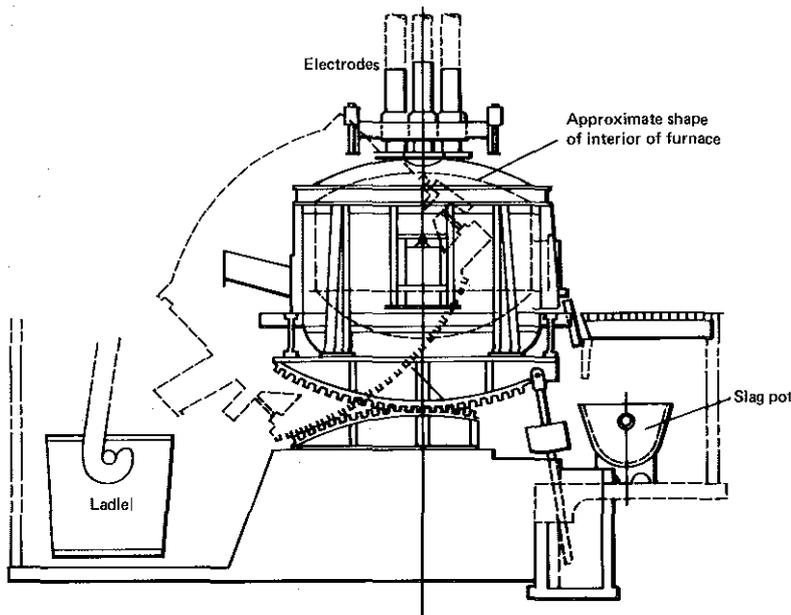


Fig. 3 Schematic diagram of electric arc furnace

The rapid growth of the submerged tuyere processes is also reflected in the parallel growth of postrefining processes. One specific example is the argon-oxygen decarburization process (AOD), which uses an inert gas in the outer tuyere and an oxidizing gas in the inner tuyere. This process has rapidly achieved adoption for duplex refining of stainless steel and more recently for alloy grades. In addition, the process has gained rapid adoption throughout the foundry industry as a means for completing refining of small heats of a wide range of steels and alloys.

Comparing the top- and bottom-blown processes from an operational viewpoint brings out certain advantages for each. Because of lower plant height required for the bottom-blown process, the minimum cost is less either for a green-field site or for conversion of an open-hearth or Bessemer shop. However, the scrap-melting capability of the bottom-blown process is less, compared with the top-blown process, because of the lower iron oxide content of the slag, a factor that can be looked upon as representing an increase in process yield.

Combined top and bottom blowing is currently being explored to combine the advantages of each type of oxygen steelmaking. These early tests have shown higher yield, improved manganese recovery, better control of oxygen content, and lower oxygen concentrations, as well as improved dephosphorization.

Electric Furnace Steelmaking. The electric arc furnace is used primarily for the production of carbon and alloy engineering steels and also as the primary melting stage in the production of stainless steels. The principal raw material for the electric arc furnace is recycled steel scrap, which makes the process environmentally friendly and also energy efficient compared with production from iron ore.

Any one of several types of electric furnaces may be used in the manufacture of steel products. However, the most commonly used types are the electric arc furnace and the induction furnace. Of these two types, the electric arc furnace is used far more extensively. Induction melting generally is used for producing relatively small quantities of specialty steels or for remelting and refining special alloys.

The electric arc furnace usually is built to operate in air; the other furnaces can be built to operate in air or as vacuum furnaces. Because electric furnaces can be conveniently built to a small scale, they can be used in small-scale steelmaking operations. Because they do not require molten pig iron in the charge, they also are used in facilities that are not located near blast furnaces. In certain installations, electric furnaces are less costly to install and operate than are basic oxygen or open-hearth equipment. Electric furnaces can be used for producing specialty steels, such as tool steels, stainless steels, and aircraft-quality steels, or for manufacturing the common grades of carbon and alloy steels.

The electric arc furnace, shown schematically in Fig. 3, is the most widely used type of electric furnace; for steelmaking, a basic refractory lining is usually used. Three carbon electrodes extending through the roof contact the metal charge; three-phase alternating current flows through the metal between the electrodes. The charge usually includes cold pig iron, scrap, and virgin materials such as ingot iron and ferroalloys. The acid-lined electric arc furnace is most often used in the production of steel castings.

Ladle Metallurgy

Regardless of which steelmaking process is used, removal of reaction products from the molten steel during the deoxidation process is most critical. Nonmetallic inclusions in the form of

oxides of silicon, manganese, and aluminum may influence final properties adversely.

Sulfur in steel has presented a problem in steelmaking from the very beginning. Improved surface quality can be achieved by lowering sulfur levels to 0.015% or less. The achievement of low sulfur content in steelmaking—for example, by use of two slag practices in electric furnaces—has presented operating difficulties and production delays.

In killed steels with low oxygen content, for example when aluminum is used for deoxidation and grain-size control, sulfur combines with manganese in the form of highly deformable manganese sulfides. These manganese sulfides have a low melting point and, as the last liquid to solidify in the steel, collect as films at grain boundaries. During hot rolling, the manganese sulfides are plastically deformed into elongated stringers extending parallel to the rolling direction. This shape and distribution of sulfides can have a marked negative effect on the directional properties of steel products. Two methods can be used to minimize the influence of the total volume of sulfide inclusions in the steel product. This can be accomplished by decreasing the total sulfur input, treating the hot metal to remove sulfur, and controlling the scrap charge; by adjusting melting practices, including the use of additional quantities of flux; and by direct treatment of the liquid steel with desulfurizing agents, such as calcium or magnesium. A second approach involves modifying the shape or morphology of sulfide inclusions by producing a relatively nondeformable complex sulfide and/or oxysulfide by addition of calcium or rare earth metals.

Ladle metallurgy was first used to produce high-quality steels, but is now being utilized for many grades of steel because of the economic advantages of higher productivity. Ladle treatments of steel can be described generally in five categories:

- Synthetic slag systems
- Gas stirring or purging
- Direct immersion of reactants, such as rare earths
- Lance injection of reactants
- Wire feeding of reactants

These are often used in combination to produce synergistic effects, for example, synthetic slag and gas stirring for desulfurization followed by direct immersion, injection, or wire feeding for control of inclusion shape.

Synthetic Slag Systems. Addition of a prepared flux layer to the steel ladle during or immediately following tapping offers an opportunity to accomplish specific refining reactions. To prevent reversion of undesirable elements, such as phosphorus, sulfur, and oxygen, from the steelmaking slag, as little slag as possible should be allowed to escape from the furnace into the ladle. However, prevention of heat loss requires that some thermal insulation cover the steel in the ladle. This can be achieved with considerable advantage using a fluid, sulfur-free, highly reac-

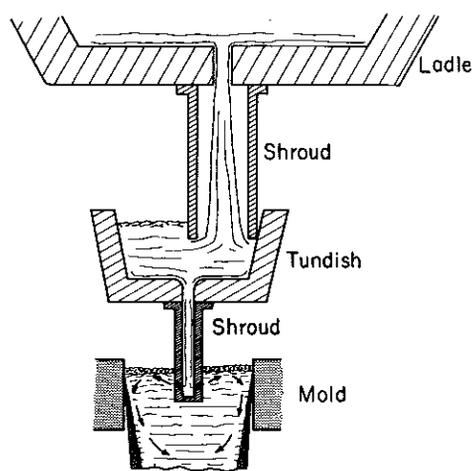


Fig. 4 Schematic of a shrouding system for minimizing oxidation during pouring

tive synthetic slag. The basicity can be controlled and desulfurization achieved. Materials currently in use generally are based on the calcia-alumina system with additions of fluorspar and perhaps a small amount of a reducing agent such as carbon, aluminum, or calcium silicide. Promotion of desulfurization can be achieved by good mixing and stirring of the system by a gas stream or by induction stirring. These materials must be dry to minimize hydrogen pickup.

Gas Stirring and Purging. Bubbling of a gas such as nitrogen, or in appropriate circumstances the more expensive gas argon, through the steel ladle will promote flotation of inclusions and provide homogeneity of temperature and composition following the addition of ladle additives and deoxidizers. Gas or induction stirring also creates local metal currents flowing vertically downward, aiding in recovery of buoyant additions made by plunging or wire injection.

Immersion. Reactants can be added to molten steel, for example, by plunging a canister containing the reagent.

Lance Injection. Several processes are currently in use for injection of solid particulate metallic reactants such as magnesium, calcium, calcium-silicon, ferrosilicon, aluminum, or elements for microalloying; nonmetallic fluxes, such as CaO or CaO-Al₂O₃; or mixtures of these additions. These systems generally use a refractory-coated lance immersed deep in the ladle and are based on dense-phase transport. They use less than 30% gas by volume, which causes relatively little disturbance of the bath for injection of a substantial amount of reactant. The capital and operating costs for lance injection are generally higher than those for alternative systems, and this technique may show lower efficiencies because the lighter reactants tend to float out in the gas-bubble stream.

Wire Feeding. Solid reactants in wire form or as a wire core can be fed directly into the steel ladle, into the casting tundish or, under some circumstances, directly into the mold—all yielding a high recovery of the reactant. The operating costs for these systems are relatively low, de-

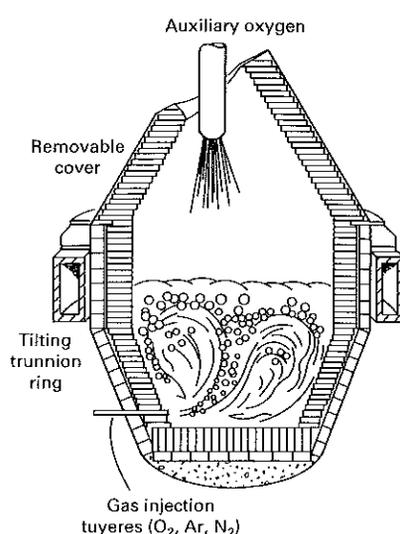


Fig. 5 Schematic of argon-oxygen decarburization vessel

pending primarily on the economics of reactant preparation.

A basic or neutral (high-alumina) ladle lining is required for desulfurization to low levels, because the reactants used will usually attack acidic linings, such as fireclay. High-alumina refractories (70 to 90% alumina) are typically used. A suggested installation is a 70% alumina lining with fine-grain magnesite refractory at the slag line.

Adoption of steel refining by ladle metallurgy permits steelmaking processes to operate at lower cost and with higher productivity while simultaneously ensuring production of high-quality steels.

Protection of Pouring Streams. Recognizing that oxygen from the environment will react readily with liquid steel, the steelmaker can avoid oxygen pickup by shrouding the liquid steel pouring stream and can minimize reoxidation by maintaining a smooth, compact pouring stream, in contrast to one that is rippled, ragged, or spraying.

There are several approaches to minimization of oxidation during pouring. One method is a shrouding system such as that shown in Fig. 4.

Refining and Remelting Processes

The principal refining and remelting processes used in production of special alloys are argon-oxygen decarburization (AOD), electroslag refining (ESR), vacuum arc remelting (VAR), and vacuum induction melting (VIM). Additional information on some of these processes can be found in the article "Effects of Steel Processing on Properties" in this Volume.

Argon-Oxygen Decarburization (AOD). The AOD process was originally developed for production of stainless steels, but rapidly found use in production of many nonstainless grades. Almost immediately it was applied to production of high-chromium, nickel-base superalloys. Since then it has been used for production of

almost all classes of steels, including low-chromium steels, cobalt-base alloys, chromium-free nickel grades, and alloys used for their expansion, resistive, and magnetic properties. The incentive for use of this process for production of low-chromium steels is its good degassing characteristics, permitting in some cases the pouring of grades sensitive to hydrogen cracking without the need for more expensive vacuum degassing, and its excellent sulfur-removal and good inclusion-removal characteristics, which provide mechanical properties superior to those obtained when only arc furnace melting is used.

The excellent carbon-removal characteristics of this process, even in the presence of high chromium, have permitted economical production of a whole class of low-carbon alloys. Originally this included extra-low-carbon versions of conventional stainless steels and nickel-base, corrosion-resistant superalloys.

AOD Equipment and Processing. Liquid metal produced in an electric arc furnace is refined in a pear-shaped, refractory-lined vessel (Fig. 5). The metal and slag fill the bottom one-third to one-half of the vessel; the large space is needed to contain the metal and slag during rapid injection of argon-oxygen mixtures into the bath. The vessel is mounted on a trunnion ring, and the entire assembly can be tilted for tapping or sampling. Attachment of the vessel to the ring is such that a vessel with worn refractories can be quickly removed and a relined vessel rapidly put in its place. The use of multiple shells permits refractory work to take place without interrupting production.

Gas is injected into the bath through two or more tuyeres located in the side and near the bottom of the vessel. They are located along the back side of the vessel so that, when the top of the vessel is tilted forward, the tuyeres are uncovered. This permits sampling and temperature measurement without blowing metal and slag through the mouth of the vessel onto operating personnel.

Each tuyere consists of two concentric tubes. An argon-oxygen mixture or pure argon is blown into the bath through the inner tube, and pure argon is blown into the bath through the annulus formed by the two tubes. Only a relatively small amount of argon is blown into the vessel through the annulus; its function is to prevent the tuyeres from rapidly eroding.

Most AOD installations are equipped with gas-handling systems capable of delivering various gas mixtures as desired. Nitrogen may be used in place of argon with substantial savings, provided that nitrogen pickup from the blown gas is not deleterious to the product.

A pit large enough to hold the teeming ladle is situated in front of the vessel. A movable platform can be placed across the pit to permit sampling and temperature measurement through the mouth of the vessel.

Electroslag Remelting (ESR). The success achieved in producing high-integrity weldments by the electroslag process led to the development of ESR for producing high-purity metals.

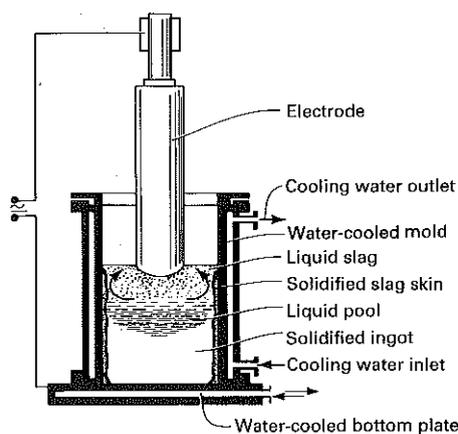


Fig. 6 Schematic of the electroslag remelting process

A schematic view of a basic ESR furnace is shown in Fig. 6. The material (electrode) to be refined is remelted by passing a current through it into a molten slag, which is resistively heated and which, in turn, melts the electrode. Molten metal droplets form on the end of the electrode and fall through the slag, forming an ingot in a water-cooled copper crucible. The process continues until the electrode is consumed and the ingot is formed. The ESR process is employed in order to improve material quality through:

- Removal of oxide and sulfide inclusions
- Control of the solidification rate and thus elimination of shrinkage porosity and minimization or elimination of segregation
- Improvement of surface quality

In general, the ESR process has been shown to be capable of accomplishing these objectives, and steels produced by the ESR technique normally exhibit better property levels and, more significantly, less scatter in these properties.

Vacuum arc remelting (VAR) is a casting process carried out in a vacuum with the objective of remelting the consumable electrode to produce an ingot that has improved chemical and physical homogeneity.

The energy that promotes remelting of the electrode is supplied by an arc that occurs between the bottom surface of the electrode (usually the cathode) and the top surface of the newly formed ingot (usually the anode). A typical VAR setup is depicted schematically in Fig. 7.

Originally, VAR was used to melt refractory metals such as tungsten, tantalum, and molybdenum, all of which required water-cooled metal molds because these metals react with ceramic molds. Electrodes of reactive metals such as titanium and zirconium are prepared by consolidating powders or metallic chunks into forms of required shape. Sometimes the initial VAR is followed by a second (and even a third) VAR step to ensure the required properties of aircraft-quality steels.

Vacuum induction melting (VIM) is the most flexible of the vacuum melting processes because it allows for independent control of temperature,

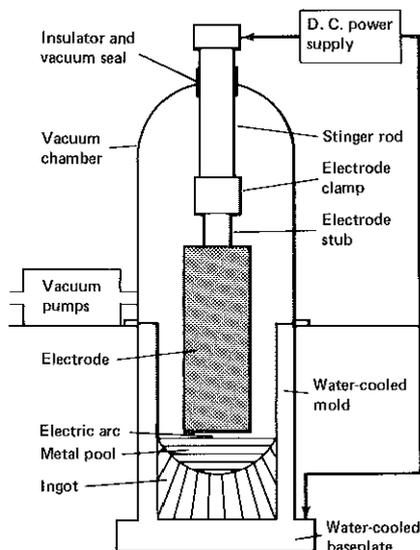


Fig. 7 Schematic diagram of vacuum arc remelting furnace

pressure, and mass transport by means of stirring. As a consequence, VIM provides the greatest degree of control over steel composition of all the melting processes, which is probably its most important metallurgical justification.

Production VIM furnaces range in size from less than 1 ton to 60 tons in melt capacity. The basic components for these units are essentially the same, as shown schematically in Fig. 8.

The basic charge is melted in an induction furnace with a rammed or brick lining. Most furnaces with melting capacities greater than 4 tons are brick lined. The frequency and power requirements are similar to those of air-melting counterparts, but every attempt is made to keep

coil voltage as low as practical to avoid corona and arcing in certain ranges of reduced pressure. Special insulating techniques also are used for this purpose.

A water-cooled metal tank is required to enclose the melting furnace. The configuration varies widely from furnace to furnace, depending on production requirements. Most large-scale furnaces have a two-chamber arrangement—one to enclose the melting furnace and the other to house the molds and their handling mechanism. These chambers usually are connected by means of large-scale vacuum valves, and each chamber has its own access doors and vacuum pumps. Therefore, melting can proceed while the molds are being set up or removed, minimizing turn-around time.

Deoxidation Practices

In the manufacture of steel from pig iron, oxygen is used to remove excess carbon from the molten metal so that the carbon content desired for the finished steel can be achieved. Carbon and oxygen, both dissolved in the liquid metal, combine to form carbon monoxide, which bubbles to the surface of the melt. Sources of the dissolved oxygen are the excess present in the atmosphere above the melt, that contained in materials added to the slag or molten metal, or that present as a product of chemical reactions that occur during steelmaking. Two problems can result from oxygen that remains dissolved in the melt after the carbon content is reduced to the desired level: The carbon and oxygen may continue their combination reaction during solidification, or the oxygen content of the finished steel may be unacceptably high. Some sort of deoxidation procedure is often used during the manufacture of steel. Steels, when cast into ingots, can be classified

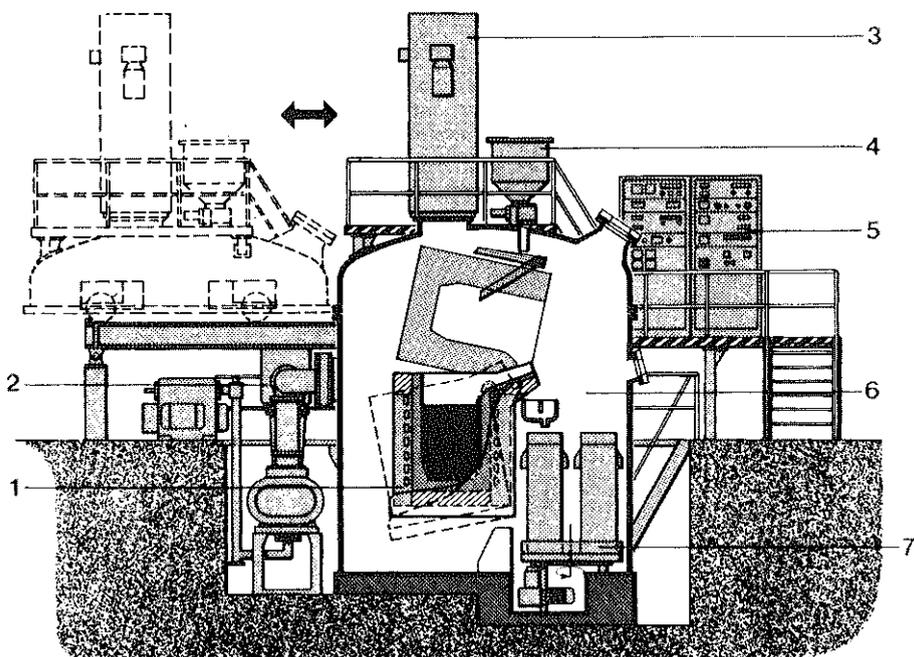


Fig. 8 Schematic of a typical vacuum induction melting furnace. 1, furnace insert; 2, vacuum pumping system; 3, bulk charger; 4, fine charger; 5, control cabinets; 6, melting and mold chamber; 7, mold turntable

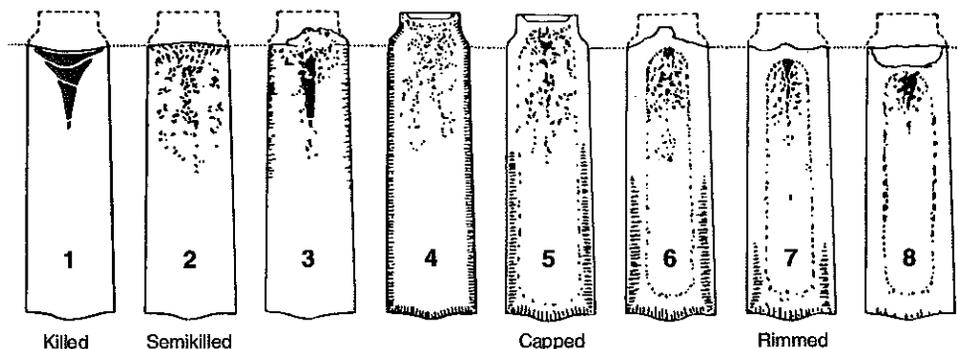


Fig. 9 Eight typical conditions of commercial steel ingots, cast in identical bottle-top molds, in relation to the degree of suppression of gas evolution. The dotted line indicates the height to which the steel originally was poured in each ingot mold. Depending on the carbon and, more importantly, the oxygen content of the steel, the ingot structures range from that of a fully killed ingot (No. 1) to that of a violently rimmed ingot (No. 8).

into four types based on the deoxidation practice employed or, alternatively, by the amount of gas evolved during solidification. If little or none is evolved, the steel is termed "killed," because it lies quietly in the mold. Steels having increasing degrees of gas evolution are termed "semikilled," "capped," or "rimmed." Vacuum treatment can also be used to deoxidize steels. Figure 9 compares eight typical conditions of deoxidized ingots.

Vacuum treatment can also be used to deoxidize steels. Information on vacuum degassing processes can be found in the article "Effects of Steel Processing on Properties" in this Volume and in the article "Degassing Processes (Ladle Metallurgy)" in Volume 15 of the *ASM Handbook*.

Killed steels are produced by adding deoxidizing elements such as silicon and aluminum to the ladle before pouring. Although silicon and aluminum are the most common deoxidizing elements, vanadium, titanium, and zirconium are also sometimes used. These elements combine preferentially with the oxygen in the melt, producing silica and alumina, much of which is mixed into the slag.

Killed steels solidify with a rather large shrinkage pipe in the center of the ingot (Fig. 9); effects of the shrinkage pipe on the finished mill products can be minimized by pouring the ingot large end up and using a hot top, which confines most shrinkage to the subsequently discarded hot top. Chemical composition and mechanical properties

of killed steels are relatively uniform throughout the ingot, although some variation must be expected. Alloy and carbon steels containing more than about 0.25% C are almost always fully killed.

Killed Steels with Inclusion Shape Control.

All steels contain small amounts of nonmetallic inclusions, primarily sulfides, silicates, and oxidized materials. They are derived chiefly from the oxidizing reactions of the refining and casting processes, and some may result from erosion of refractories during tapping or pouring. Sulfide inclusions are the most deleterious to the formability of steels, because they elongate during hot rolling, creating longitudinal stringer-type inclusions that adversely affect the transverse ductility of the steel. This becomes increasingly important in high-strength steels, which have an initial overall ductility that is already lower.

Practices have been developed to minimize this hazard by adding elements (zirconium, titanium, calcium, or rare earth elements) to the steel that combine with sulfur to create hard, globular inclusions that do not elongate during hot rolling, thereby improving the transverse ductility of the steel. The steel industry is moving toward a greater use of desulfurization steelmaking practices, in which the steel sulfur levels are being significantly reduced so that sulfide inclusions are almost eliminated. Either of these practices (shape control or desulfurization) will improve the formability of killed steels beyond their existing level.

Semikilled steel is a type of steel wherein there is a greater degree of gas evolution than in killed steel but less than in capped or rimmed steel. The amount of deoxidizer used (customarily silicon or aluminum) will determine the amount of gas evolved. Semikilled steels generally have a carbon content within the range of 0.15 to 0.30%; they are used for a wide range of structural shape applications.

Semikilled steels are characterized by variable degrees of uniformity in composition, which are intermediate between those of killed and rimmed steels. Semikilled steel has a pronounced tendency for positive chemical segregation at the top center of the ingot (Fig. 9).

Rimmed steels are cast into ingots without deoxidation by silicon or aluminum; they are not killed. As solidification of a rimmed steel ingot proceeds, oxygen and carbon dissolved in the molten metal continue to combine, producing a characteristic effervescent action in the ingot during solidification. The much lower solubility of oxygen in solid steel compared with that in liquid steel also contributes to the effervescence.

Rimmed steel ingots are less likely to have large shrinkage pipes than are killed steel ingots; some shrinkage porosity, however, normally exists in the former (Fig. 9). Chemical composition and mechanical properties vary widely throughout rimmed steel ingots. The region near the surface of a rimmed steel is lower in carbon, sulfur, and phosphorus than the average composition of the ingot. The low-carbon skin on a rimmed steel ingot persists to the finished mill product; it generally provides a smoother surface than might be expected on a fully killed steel, although high-quality surfaces can be routinely obtained on killed steel products. Rimmed steel products, particularly cold-rolled steel sheet, can be advantageously used wherever extensive cold forming or superior surface appearance is required. Because carbon content in excess of 0.25% or manganese content greater than 0.60% prevents proper rimming action, only low-carbon steels are used for rimmed steels.

Capped steels have characteristics similar to those of rimmed steels, but to a degree intermediate between those of rimmed and semikilled steels (Fig. 9). A deoxidizer may be added to effect a controlled rimming action when the ingot is cast. The gas entrapped during solidification is in excess of that needed to counteract normal

Table 3 U.S. raw steel production by steel grade, type of furnace, and casting method

See also Table 2.

Year	Total all grades, net tons $\times 10^3$				Total production							Production by type of cast, net tons $\times 10^3$		
	Carbon	Alloy	Stainless	Total	By grade, %			By furnace type, %			Ingots	Continuous cast	Steel casting	
					Carbon	Alloy	Stainless	Open hearth	Basic oxygen process	Electric				
1992	82,458	8,498	1,993	92,949	88.7	9.2	2.1	...	62.0	38.0	19,207	73,718	24	
1991	77,879	8,139	1,878	87,896	88.6	9.3	2.1	1.6	60.0	38.4	21,166	66,666	64	
1990	86,590	10,279	2,037	98,906	87.5	10.4	2.1	3.5	59.1	37.4	32,189	66,643	74	
1989	86,230	9,786	1,926	97,943	88.0	10.0	2.0	4.5	59.6	35.9	34,412	63,454	77	
1988	86,823	10,902	2,199	99,924	86.9	10.9	2.2	5.1	58.0	36.9	38,615	61,232	77	

Source: American Iron and Steel Institute

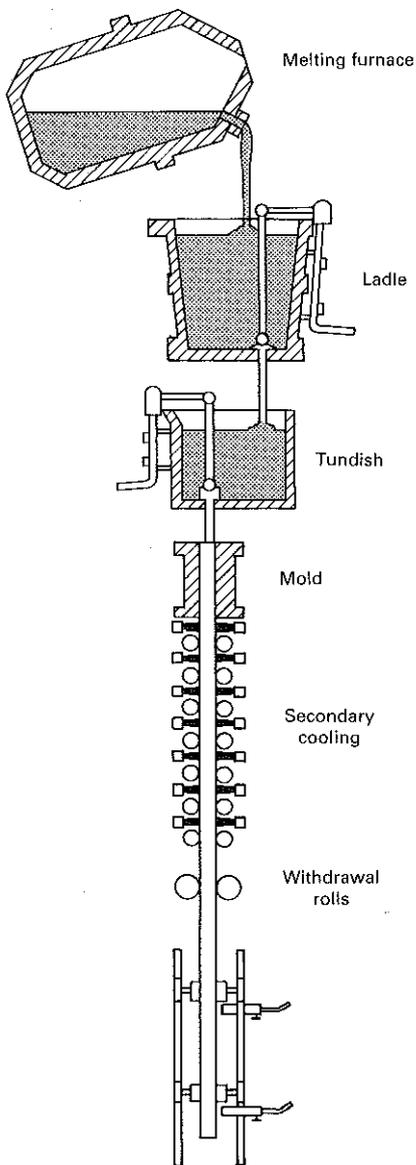


Fig. 10 Main components of a continuous casting strand

shrinkage, resulting in a tendency for the steel to rise in the mold. The capping operation limits the time of gas evolution and prevents the formation of an excessive number of gas voids within the ingot.

Mechanically capped steel is cast in bottle-top molds using a heavy metal cap.

Chemically capped steel is cast in open-top molds. The capping is accomplished by adding aluminum or ferrosilicon to the top of the ingot, causing the steel at the top surface to solidify rapidly. The top portion of the ingot is discarded.

The capped ingot practice is usually applied to steel with carbon content greater than 0.15% that is used for sheet, strip, wire, and bars.

Casting

When metal is teemed (poured) into molds, it becomes either an ingot or a casting. In reality, an

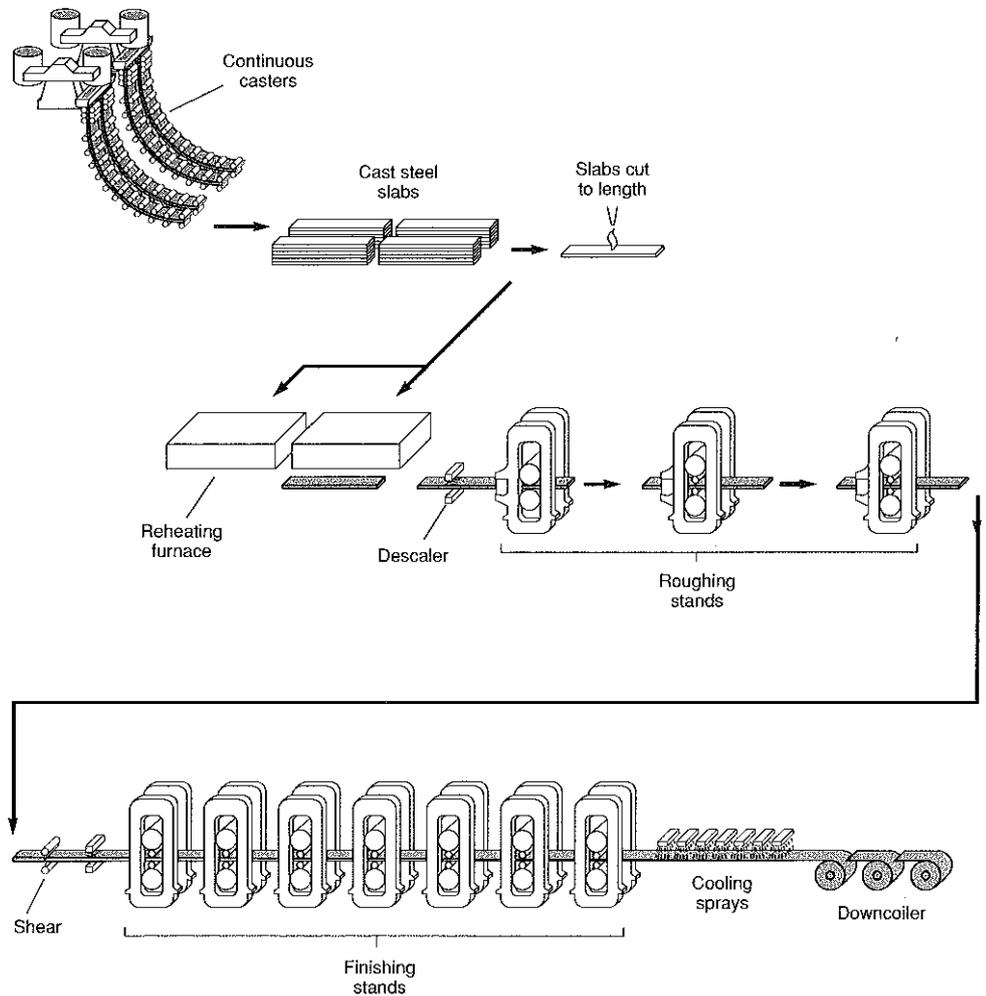


Fig. 11 Sequence of operations for flat rolling

ingot is a casting, because it is prone to all the structural characteristics of castings (shrinkage, porosity, presence of inclusions, segregation, and nonhomogeneous grain size). However, if the "casting" is to be mechanically worked (or wrought) by rolling, forging, or hammering, it is known as an ingot. If the "casting" is in the desired shape and requires only machining, it is a true casting and a typical foundry product.

As an alternative, steel may be continuously cast into any one of several product forms. Table 3 compares steel production by the type of casting process. As this table indicates, continuous cast products account for nearly 80% of the steel produced in the United States.

Continuous Casting of Steel. In the continuous casting process, molten steel is poured at a steady rate into a water-cooled mold.

Depending on the size of the product cast, a shell 3.2 to 12.7 mm ($\frac{1}{8}$ to $\frac{1}{2}$ in.) forms quickly by solidification at the mold wall. As molten metal is poured into the top of an oscillating mold to a predetermined level, the casting is withdrawn at a controlled rate from the bottom of the mold (see Fig. 10). The solidified shell acts as a container for the still-molten metal inside the casting.

As the casting is withdrawn from the mold, the cast billet, bloom, or slab is sprayed with water to cool and solidify it further. A flying shear or torch cuts the casting off at a level below which the metal has solidified.

Nearly all steels continuously cast today are killed, with typical compositions ranging from low-carbon grades for sheet and strip to medium-carbon grades in the range of 0.2 to 0.6% C, with manganese content of more than 0.6% for plate applications. Extensive experiments for casting rimming steels were conducted at several steel-producing plants, but the cost and the precise control necessary to produce a sound rim zone made this process noncompetitive.

Continuous casting has a greater metal yield than does conventional ingot-mold practice, which results in reduced fuel requirements and greater productivity. The hot metal yield in conventional ingot practice is about 87%; in continuous casting of billets, the yield is 94 to 98%, depending on the tonnage of the heat and the cross-sectional shape of the product cast.

The process allows casting of special cross-sectional shapes, such as dumbbell or dogbone shapes for rolling into structural sections.

The quality of the cast product is uniform and good to excellent. Scarfing is reduced, and often eliminated. The product is comparatively free from macrosegregation, grain size is easy to control, steel cleanliness is equal to or better than that obtained in ingot-mold practice, and the product withstands severe hot reduction. The cost of equipment is relatively low; small-tonnage mills are feasible, and there is a major savings in large-tonnage plants. Additional information on the continuous casting process can be found in Volume 15 of the *ASM Handbook* (see pages 308 to 316).

Hot Rolling

As with liquid steel, several processing operations are required to convert solid steel into its wide variety of finished forms. Figure 11 shows the sequence of operations for flat rolling. After continuous casting and inspection, followed by slab reheating in the reheat furnace, the slab is prepared for the roughing and tandem (finishing) hot strip mills. Rolled hot strip is then cooled on runout cooling tables and coiled. For thinner gages, hot-rolled strip is cold-rolled, which is followed by annealing and by various coating processes to protect against corrosion. Slabs cut from the continuous casting machine are reheated to bring the steel to about 1200 °C (2190 °F).

The actual rolling operation consists of passing the steel ingot (or bloom, slab, or billet) between two rolls revolving in opposite directions at the same speed and so spaced that the distance between them is somewhat less than the thickness of the piece of steel entering them. The rolls grip the steel, reduce it in cross-sectional area, and deliver it increased in length. The spread (the extent of lateral spreading) depends chiefly on the amount of reduction and the shape of the section entering the rolls. Details on the mechanical deformation that occurs during rolling can be found in the article "Flat, Bar, and Shape Rolling" in Volume 14 of the *ASM Handbook*.

Effects of Alloying Elements

Alloying elements are added to steels to effect changes in the properties of the steels. A semantic distinction can be made between alloying elements and residual elements, which are not intentionally added to the steel, but result from the raw materials and steelmaking practices used to produce the steel. Any particular element may be either alloying or residual. For example, some nickel or chromium could come into steel through alloy steel scrap and so be considered residual; however, if either of these elements must be added to a steel to meet the desired composition range, it might be considered an alloying element.

Both alloying and residual elements can profoundly affect steel production, manufacture into end products, and service performance of the end product. The effects of one alloying element on a steel may be affected by the presence of other elements; such interactive effects are complex. In

addition, the effects of a particular element may be beneficial to steel in one respect but detrimental in others. General effects of the various alloying and residual elements commonly found in steels are summarized below.

Carbon is the most important single alloying element in steel. It is essential to the formation of cementite (and other carbides), pearlite, spheroidite (an aggregate of spherical carbides in a ferrite matrix), bainite, and iron-carbon martensite. Microstructures comprising one or more of these components can provide a wide range of mechanical properties and fabrication characteristics. The relative amounts and distributions of these elements can be manipulated by heat treatment to alter the microstructure, and therefore the properties, of a particular piece of steel. Much of ferrous metallurgy is devoted to the various structures and transformations in iron-carbon alloys; many other alloying elements are considered largely on the basis of their effects on the iron-carbon system.

Assuming that the comparisons are made among steels having comparable microstructures, the strength and hardness are raised as the carbon content is increased; however, toughness and ductility are reduced by increases in

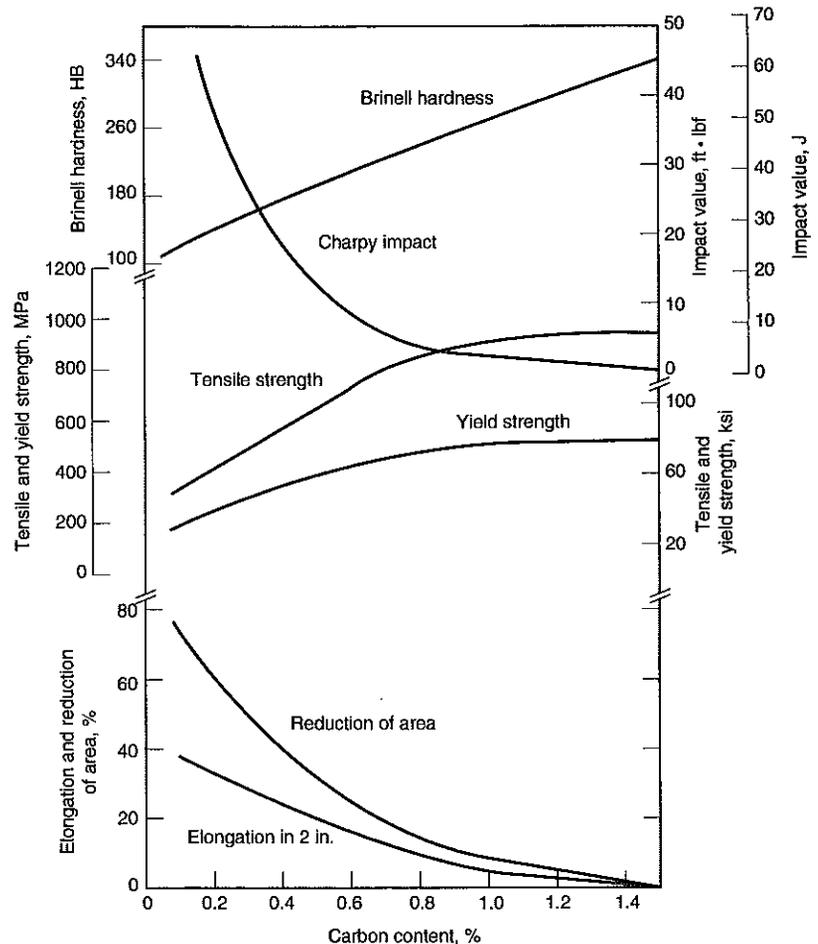


Fig. 12 Variations in average mechanical properties of as-rolled 25 mm (1 in.) diam bars of plain carbon steels, as a function of carbon content

carbon content. The influence of carbon content on mechanical properties is shown in Fig. 12. The hardness of iron-carbon martensite is increased by raising the carbon content of steel, reaching a maximum at about 0.6% C. Increasing the carbon content also increases hardenability. More detailed information on the effects of carbon content on strength and hardenability characteristics can be found in the articles "Microstructure/Property Relationships in Steels" and "Hardenability of Steels," respectively, in this Volume.

The amount of carbon required in the finished steel limits the type of steel that can be made. As the carbon content of rimmed steel increases, surface quality becomes impaired. Killed steels in approximately the 0.15 to 0.30% C content level may have poorer surface quality and require special processing to obtain surface quality comparable to steels with higher or lower carbon content. Carbon has a moderate tendency to segregate, and carbon segregation is often more significant than the segregation of other elements.

Manganese is normally present in all commercial steels. It is important in the manufacture of steel because it deoxidizes the melt and facilitates hot working of the steel by reducing the susceptibility to hot shortness. Manganese also com-