Primary Mill Fabrication

A GENERAL DIAGRAM for the production of steel from raw materials to finished mill products is shown in Fig. 1. Steel production starts with the reduction of ore in a blast furnace into pig iron. Because pig iron is rather impure and contains carbon in the range of 3 to 4.5 wt%, it must be further refined in either a basic oxygen or an electric arc furnace to produce steel that usually has a carbon content of less than 1 wt%. After the pig iron has been reduced to steel, it is cast into ingots or continuously cast into slabs. Cast steels are then hot worked to improve homogeneity, refine the as-cast microstructure, and fabricate desired product shapes. After initial hot rolling operations, semifinished products are worked by hot rolling, cold rolling, forging, extruding, or drawing. Some steels are used in the hot rolled condition, while others are heat treated to obtain specific properties. However, the great majority of plain carbon steel products are low-carbon (<0.30 wt% C) steels that are used in the annealed condition. Medium-carbon (0.30 to 0.60 wt% C) and high-carbon (0.60 to 1.00 wt% C) steels are often quenched and tempered to provide higher strengths and hardness.

Ironmaking

The first step in making steel from iron ore is to make iron by chemically reducing the ore (iron oxide) with carbon, in the form of coke, according to the general equation:

\[ \text{Fe}_2\text{O}_3 + 3\text{CO} \rightarrow 2\text{Fe} + 3\text{CO}_2 \]  

(Eq 1)

The ironmaking reaction takes place in a blast furnace, shown schematically in Fig. 2, which is essentially a tall, hollow, cylindrical structure with a steel outer shell lined on the inside with refractory brick. The raw materials for a blast furnace charge are iron ore, coking coal, and fluxes, mainly limestone. Coke is a spongelike carbon mass that is produced from coal.
Fig. 1 Principal steps in steelmaking. Source: Ref 1
by heating coal to expel the organic matter and gases. In a process called carbonization, blended coal is first heated in ovens to produce coke. The gas produced during carbonization is extracted and used for fuel elsewhere in the steelworks. Other by-products, such as tar, are also extracted for further refining and sale. After carbonization, the coke is pushed out of the ovens and cooled. Limestone, mainly calcium carbonate, is added as a flux for easier melting and slag formation. The slag floats on top of the molten iron and absorbs many of the unwanted impurities. Fine ore is mixed with the coke and fluxes and heated in a sinter plant on a continuous moving belt on which the coke is ignited. The high temperatures generated fuse the ore particles and fluxes together to form a porous clinker called sinter. The use of sinter in the blast furnace helps make the ironmaking process more efficient.

Iron ore lumps and pellets, coke, sinter, and possibly extra flux are carried to the top of the blast furnace on a conveyor and charged into the furnace. The crushed or pelletized ore, coke, and limestone are added as layers through an opening at the top of the furnace. Hot air at approximately 900 °C (1650 °F) is blasted into the bottom of the furnace, an area
called the bosh, through water-cooled copper nozzles called tuyeres. The oxygen in the air reacts with the coke to form carbon monoxide gas according to Eq 1 and, at the same time, generates a great deal of heat.

Frequently, oil or coal is injected with the air, which allows less expensive coke to be used. The carbon monoxide gas flows up through the blast furnace, removing oxygen from the iron ore and leaving iron. The iron in the ore reduces to metallic iron from iron because the free energies of CO and CO$_2$ are both lower than that of iron oxide. This greatly increases the temperature and provides the required carbon for steelmaking.

The resulting liquid iron is tapped at regular intervals by opening a hole in the bottom of the furnace, and the hot metal flows into specially constructed railway containers that transport the liquid iron to the basic oxygen furnace (BOF), where it is made into steel. The molten slag, which floats on the iron, is removed by tapping at regular intervals. A successful steelmaking furnace campaign can last for ten continuous years or more. If the furnace were allowed to cool, damage to the refractory lining bricks could result from their contraction as they cooled. Eventually, the refractory brick linings are eroded away, the steelmaking campaign is stopped, and the furnace is relined with new bricks.

**Steelmaking**

The two dominant steelmaking methods during the 20th century were the Bessemer and open-hearth processes. In the Bessemer process, developed in 1856, air was blown through molten pig iron to reduce the carbon and silicon contents to tolerable levels. In the open-hearth processes, developed shortly after in 1858, steel was made in a very large, shallow furnace in which carbon reduction was achieved by an oxidizing slag. Although the open-hearth furnace required a longer time (8 h versus 30 min for the Bessemer process), it was more widely used because much larger amounts of steel could be produced. Both of these processes are now obsolete, and the basic oxygen furnace (BOF) has largely replaced both of these older processes.

**Basic Oxygen Furnace (BOF)**

Most modern bulk steels are made in the BOF according to the process shown in Fig. 3. Up to 30% of the BOF is charged with scrap steel, followed by liquid pig iron from the blast furnace. A water-cooled lance is then lowered into the vessel, through which very pure oxygen is blown at high pressure. The oxygen interacts with the molten pig iron to oxidize undesirable elements, including excess carbon, manganese, and silicon from the ore, limestone, and other impurities such as sulfur and phosphorus. Carbon in the steel reacts with iron oxide to form iron and carbon monoxide:
FeO + C → Fe + CO  \hspace{1cm} (Eq 2)

A careful balance between the relative amounts of pig iron and scrap charged into the converter is maintained as a means of controlling the temperature and to ensure that steel of the required specification is produced. After a sample has been taken to verify the chemical composition of the steel, the vessel is tilted to allow the molten steel to flow out. The steel is tapped into a ladle where further composition adjustments are made. During tapping, small quantities of other metals and fluxes are often added to control the state of oxidation and to meet requirements for particular grades of steel. Finally, the vessel is turned upside down to remove the remaining slag. A modern BOF vessel can make up to 318,000 kg (700,000 lb) of steel in approximately 40 min with the desired carbon content and a low level of impurities such as sulfur and phosphorus.

While in the ladle, certain alloying elements can be added to the steel to control the state of oxidation and produce the desired chemical com-
position. The ladle furnace is maintained at a specified temperature by external heat from electrodes in the lid that covers the ladle. After the desired chemical composition is achieved, the ladle can be placed in a vacuum chamber to remove undesirable gases such as hydrogen and oxygen. Degassing is used for higher-quality steel products, such as railroad rail, sheet, plate, bar, and forged products.

**Electric Arc Furnace (EAF)**

Unlike the BOF, the EAF (Fig. 4) does not use molten pig iron but uses steel scrap. Steel scrap is charged into the furnace from an overhead crane, and a lid is swung into position over the furnace. The lid holds graphite electrodes that are lowered into the furnace. An electric current is passed through the electrodes to form an arc, which generates the heat necessary to melt the scrap. During melting, alloying elements are added to the steel to give it the required chemical composition. After samples have been taken to check the chemical composition, the furnace is tilted to allow the floating slag to be poured off. The furnace is then tilted in the other direction, and the molten steel is tapped into a ladle, where it either undergoes secondary steelmaking or is transported to the caster. The modern electric arc furnace typically makes approximately 136,000 kg (300,000 lb) of steel in about 90 min.

![Fig. 4](image_url) Schematic cross section of a typical electric arc furnace showing the application of different refractories. Source: Ref 3
Because the EAF has a relatively low capital equipment cost and uses steel scrap, this process is used where local supplies of steel scrap are available (almost everywhere) and has given rise to what are known as “mini” mills. The EAF is used for producing alloy steels that contain appreciable amounts of easily oxidized alloying elements, such as chromium, tungsten, and molybdenum. It can also be used to make steels requiring very low sulfur and phosphorus contents. Special slags are used to lower the sulfur and phosphorus levels and to protect against oxidation of alloying elements. An additional benefit is that temperature control with the electric arc process is very good.

**Ladle Metallurgy**

The demand for higher-quality and cleaner steels has led to refining operations after the steel is made by either the basic oxygen or electric arc processes. These refining processes are conducted in the liquid steel transfer ladle into which the steel has been poured after the basic oxygen or electric arc processes are complete. By conducting these refining processes outside the steelmaking furnace, valuable steelmaking resources are freed up. In addition, reducing atmospheres are more easily applied for desulfurization. Vacuum degassing is also possible with the steel in a ladle, and argon lances can be used to stir the steel to make the composition more homogeneous. Vacuum degassing produces ultralow-carbon steels, with carbon contents as low as 0.002 wt%. This allows these ultralow-carbon steels to be continuously annealed and have the high formability required for deep-drawing applications. Vacuum degassing also removes hydrogen that can result in hydrogen flaking and porosity.

**Residual Elements and Cleanliness**

Various manufacturing practices can affect the oxygen, nitrogen, and sulfur contents and hence the cleanliness of the product. Cleanliness usually refers to the nonsteel phases, such as oxides, sulfides, and silicates that can be present in steel. The smaller the amount of these phases, the cleaner the steel. They are present in the form of inclusions that can have significant undesirable effects on the properties of steel. Tin, antimony, arsenic, and copper are considered residual or tramp elements in steel, although copper can be added as an alloying element to improve the corrosion resistance of some steels. Tramp elements remain in steel because they are difficult to remove during steelmaking and refining. Steels made by electric furnace melting employing scrap as a raw material contain higher levels of residual elements than steels made in an integrated steelmaking facility using the blast furnace-BOF route. Some electric furnace melting shops use direct reduced-iron pellets to dilute the effect of these residuals.
Hydrogen is also a residual element that can be very deleterious. Hydrogen is soluble in liquid steel and somewhat soluble in austenite. However, it is insoluble in ferrite and is rejected as atomic hydrogen (H\(^+\)). If trapped inside the steel, usually in products such as thick plate, heavy forgings, or railroad rail, hydrogen will accumulate on the surfaces of manganese sulfide inclusions. Eventually, enough molecular hydrogen (H\(_2\)) accumulates and sufficient pressure develops to create internal cracks. As the cracks grow, they form what are termed hydrogen flakes, and the product must be scrapped. However, if the product is slow cooled from the rolling temperature, atomic hydrogen has sufficient time to diffuse out of the product, thus avoiding hydrogen damage. Vacuum degassing is used to remove hydrogen from liquid steel.

There have been major advances in the production of steel during the last 30 years, and continuous casting, in which great attention is being paid to the cleanliness of the steel, has become the dominant production method. Vacuum deoxidation is also being used to eliminate oxygen, and the steel is protected by argon atmospheres in covered tundishes that yield cleaner steel with a lower inclusion content. This is beneficial to the mechanical properties and uniformity of the final product. Continuous casting also produces a product that is much closer to a shape that is amenable to hot rolling.

More and more steel sheet is now being produced by minimills. These mills, employing electric arc furnaces, continuously cast steel into slabs several inches thick and a few feet wide. The slab is immediately fed through a long furnace to the hot rolling mill. However, because steel scrap is the primary raw material, controlling the residual elements in the composition can be problematic. Copper is particularly troublesome because it is not easily removed from liquid steel, and, as its concentration increases, it can produce cracks due to hot shortness by penetrating the grain boundaries and causing grain-boundary cracking during hot rolling. Hot shortness is the tendency for alloys to separate along grain boundaries when stressed or deformed at temperatures near the melting point. Hot shortness is caused by a low-melting constituent, often present only in minute amounts, that has segregated to the grain boundaries.

**Alloy Steel Refining**

High-strength steels are available in a variety of quality levels, depending on the type of melting practice used. While many of these steels were originally air melted, the trend has been to move to more advanced melting techniques such as vacuum degassing, electroslag remelting (ESR), vacuum arc remelting (VAR), and double vacuum melting (vacuum induction melting followed by vacuum arc remelting, or VIM-VAR) for improved cleanliness and higher quality. Since the mid-1970s, improvements in melting process control and inspection have steadily increased
fracture toughness, ductility, and fatigue resistance. A comparison of air- and vacuum-melted high-strength 300 M steel, shown in Fig. 5, illustrates the property advantages imparted by vacuum processing. Both VAR and ESR are acceptable melting methods, because the mechanical properties are essentially equivalent for both methods.

**Vacuum Induction Melting (VIM)**

Melting under vacuum in an induction-heated crucible is a tried and tested process in the production of liquid metal. It has its origins in the middle of the 19th century, but the actual technical breakthrough occurred in the second half of the 20th century. Commercial vacuum induction melting (VIM) was developed in the early 1950s, having been stimulated by the need to produce superalloys containing reactive elements within an evacuated atmosphere. The process is relatively flexible, featuring the independent control of time, temperature, pressure, and mass transport through melt stirring.

![Fig. 5](Comparison of air- and vacuum-melted 300M steel. Source: Ref 4)
A VIM furnace is simply a melting crucible inside a steel shell that is connected to a high-speed vacuum system (Fig. 6). The heart of the furnace is the crucible (Fig. 7) with heating and cooling coils and refractory lining. Heating is done by electric current that passes through a set of induction coils. The coils are made from copper tubing that is cooled by water flowing through the tubing. When an alternating current is applied to the induction coil, it produces a magnetic field, which in turn generates a current flow through the material charge, heating and finally melting it. A second magnetic field is created by the induced current in the charge. Because these two fields are always in opposite directions, they create a mechanical force that is perpendicular to the lines of flux and cause metal movement, or stirring, when the charge is liquified. As such, VIM offers more control over alloy composition and homogeneity than other vacuum melting processes. The optimal induction coil frequency varies with the charge shape, size, and melt status (liquid or solid). Older equipment used a single frequency, but newer power supplies are able to be operated at variable frequencies and are adjusted throughout the melt to obtain the most rapid heating/melting conditions.

The charge generally consists of three portions:

- A virgin portion, which consists of material that has never been vacuum melted

Fig. 6 Basic elements of a vacuum induction melting furnace. Source: Ref 5