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

Fig. 2 The iron blast furnace. Source: Ref 1
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:
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-

\[
\text{FeO + C} \rightarrow \text{Fe} + \text{CO} \quad \text{(Eq 2)}
\]
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 Schematic cross section of a typical electric arc furnace showing the application of different refractories. Source: Ref 3](image-url)
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 (H₂) 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 deoxidization 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.

![Comparison of air- and vacuum-melted 300M steel. Source: Ref 4](image)

**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](image-url)
A refractory portion, which consists of those virgin elements that are strong oxide formers and have the tendency to increase the solubility of oxides and nitrides in the virgin charge

A revert (or scrap) portion, which consists of both internal and external scrap that previously has been vacuum melted

Vacuum-melted scrap has already had its gas content reduced to levels consistent with vacuum production. Scrap, however, has the possibility of having become contaminated during the production process, and care must be taken in the segregation and preparation of scrap materials for vacuum melting.

Vacuum induction melting can be used to advantage in many applications, particularly in the case of the complex alloys employed in aerospace engineering. The following advantages have a decisive influence on the rapid increase of metal production by VIM:

- Flexibility due to small batch sizes
- Fast change of program for different types of steels and alloys
- Easy operation
- Low losses of alloying elements by oxidation
- Achievement of very close compositional tolerances
- Precise temperature control
- Low level of environmental pollution from dust output
- Removal of undesired trace elements with high vapor pressures
- Removal of dissolved gases, for example, hydrogen and nitrogen
Vacuum induction melting is indispensable in the manufacture of superalloys. Compared to air-melting processes such as electric arc furnaces with argon oxygen decarburization (AOD) converters, VIM of superalloys provides a considerable reduction in oxygen and nitrogen contents. Accordingly, with fewer oxides and nitrides formed, the microcleanliness of vacuum-melted superalloys is greatly improved compared to air EAF/AOD-melted superalloys. Additionally, high-vapor-pressure elements (specifically lead and bismuth) that may enter the scrap during the manufacture of superalloy components are reduced during the melting process. Therefore, compared to EAF/AOD-melted alloys, VIM-melted superalloys have improved fatigue and stress-rupture properties.

Control of alloying elements with VIM can also achieve much tighter levels than in EAF/AOD products. However, problems can arise in the case of alloying elements with high vapor pressures, such as manganese. Vacuum melting is also more costly than EAF/AOD melting. The EAF/AOD process allows compositional modification (reduction of carbon, titanium, sulfur, silicon, aluminum, etc.). In vacuum melting, the charge remains very close in composition to the nominal chemistry of the initial furnace charge. Minor reductions in carbon content may occur, and most VIM operations now include a deliberate desulfurization step. However, the composition is substantially fixed by choice of the initial charge materials, and these materials are inevitably higher-priced than those that are used in EAF/AOD.

Vacuum Arc Remelting (VAR) and Electroslag Remelting (ESR)

Two commonly used remelting processes for metal refinement are electroslag remelting (ESR) and vacuum arc remelting (VAR). In both processes, an electrode is melted as it advances into the melting region of the furnace. As the working face of the electrode is heated to the melting point, drops of liquid metal that fall from the electrode face are collected in a lower crucible and rapidly solidified. However, ESR and VAR have very different melting methods, which have implications regarding the magnitude of cooling rates obtained and the nature of defects created by the remelting process itself. The VAR process is carried out in a vacuum, while the ESR process typically occurs under atmospheric conditions—although electroslag remelting under vacuum (VACESR), or under pressure, is a process variation of ESR.

The VAR process is used to improve the cleanliness and refine the structure of standard air-melted or vacuum-induction-melted (VIM) ingots—typically referred to as consumable electrodes for remelting. The VAR process is also commonly used in the triplex production (VIM-ESR-VAR) of superalloys. The VAR process was the first commercial remelting process for superalloys. It was used in the late 1950s to manufacture mate-
rials for the aircraft industry. Current applications of VAR processing include the production of steels and superalloys as well as the melting of reactive metals such as titanium and zirconium alloys. The melt cleanliness and homogeneity from VAR provides benefits in both primary ingot and foundry shape casting for high-integrity applications where improved fatigue and fracture toughness of the final product are essential. This includes aerospace applications, high-strength steels, ball bearing steels, die steels, tool steels (cold and hot work steels), power generation, defense, and medical and nuclear industries.

The basic process of VAR (Fig. 8) is the continuous melting of a consumable electrode by means of a direct current arc (electrode negative, melt pool positive) in a vacuum on the order of 0.1 to 1 Pa ($7.5 \times 10^{-4}$ to 0.0075 torr). In some cases, the melting is carried out under inert gas with a pressure up to 1000 Pa (7.5 torr). Evaporation losses of volatile alloying elements are minimized at the high pressure. Remelting currents are up to 40 kA. Melting rates with VAR furnaces are as high as 1150 kg/h (2500 lb/h), and ingot diameters are as large as 1.5 m (5 ft). Most VAR furnaces have two melting stations (crucible setups). While an electrode is melting in one station, the next station is prepared for melting. When one melt is finished, the VAR head is rotated in the horizontal plane to be located over the second crucible/electrode setup.

Although the basic design of a VAR furnace has remained largely unchanged over the years, significant advances have been made in the fields of control and regulation of the process to achieve a fully automatic control system.
melting procedure. Modern VAR furnaces (Fig. 9) make use of computer-controlled process automation with continuous weighing of the consumable electrode and closed-loop process control of melting parameters, such as remelting rate and arc gap based on arc voltage or drop-short pulse rate. This has had a decisive positive influence on the metallurgical properties of the products. Close control of all remelting parameters is required for reproducible production of homogeneous ingots with controlled solidification structures free of macrosegregation.

**Electroslag remelting (ESR)** is another secondary refining process (Fig. 10), where a consumable electrode is melted by immersion in a molten flux (slag) consisting primarily of fluorspar (CaF$_2$). Heating is generated by an electrical current (usually ac) that flows from the base plate through the liquid slag and the electrode. Oxides may be added to the slag to raise the resistivity (so as to make melting more efficient electrically) or to modify the slag chemistry with regard to its reactivity with the metal being melted. Electroslag remelting is similar to VAR, except that ESR is carried out at normal atmospheric pressure and has a greater melting rate than VAR.

![Fig. 9](image_url) Modern vacuum arc remelting (VAR) furnace. (a) 30 ton VAR. (b) Operational components: 1, electrode feed drive; 2, furnace chamber; 3, melting power supply; 4, busbars/cables; 5, electrode ram; 6, water jacket with crucible; 7, vacuum suction port; 8, X-Y adjustment; 9, load cell system. Courtesy of ALD Vacuum Technologies GmbH. Source: Ref 7
When the tip of the electrode is melted by the molten slag, metal droplets fall through the liquid slag and are collected in the water-cooled mold (Fig. 10). The slag not only shields the metal pool from contaminating gases but can also be chosen so that it acts to segregate and absorb impurities from the molten metal in its passage through the slag from the electrode to the molten pool. During the formation of the liquid film, the metal is refined and cleaned of contaminants, such as oxide particles. The high degree of superheat of the slag and the metal favors the metal/
slag reaction. Melting in the form of metal droplets greatly increases the metal/slag interface surface area. The intensive reactions between metal and slag refine the melt. The remaining inclusions are very small and are evenly distributed in the remelted ingot.

The absence of macrosegregation or heterogeneity in the distribution of nonmetallic inclusions in ESR ingots justifies the additional cost of remelting. In addition, the very clean and smooth surface of ESR ingots helps to reduce production costs, because surface conditioning before hot working is not necessary. Another special feature of the ESR process, as in VAR, is the directional solidification of the ingot from bottom to top. The macrostructure is marked by an extraordinarily high density and homogeneity as well as by the absence of segregations and shrinkage cavities.

Electroslag remelting is commonly used to produce the highest levels of quality in plate steels, particularly in thick plates. The homogeneity of the ingot results in uniform mechanical properties in the longitudinal and transverse directions after hot working. For steels, the slag composition can be adjusted to serve as a desulfurizer or dephosphorizer as well as a reservoir for floating inclusions. Sulfur can be lowered to below 0.002%. The cleanliness and homogeneity of ESR ingots results in steels with excellent mechanical properties and superior toughness (Fig. 11) compared to conventionally manufactured steel. In superalloys, ESR is often used as an intermediate remelt in a so-called triple-melt process (VIM-ESR-VAR), where the ESR electrode is produced by vacuum induction melting (VIM) and then remelted a third time by VAR after ESR.

**Stainless Steel Refining**

Stainless steels are usually produced in an induction or electric arc furnace, sometimes under vacuum. To refine stainless steel, the argon oxygen decarburization (AOD) process is used. In AOD, an argon-oxygen gas mixture is injected through the molten steel to remove carbon without a substantial loss of chromium, the main alloying element in stainless steel. A premelt is prepared in an electric arc furnace by charging high-carbon ferrochrome, ferrosilicon, stainless steel scrap, burned lime, and fluor spar and melting the charge to the desired temperature. The heat is then tapped, deslagged, weighed, and transferred into an AOD vessel, which consists of a refractory-lined steel shell mounted on a tiltable trunnion ring (Fig. 12). As shown in Fig. 12, process gases (oxygen, argon, and nitrogen) are injected through submerged, side-mounted tuyeres. The dilution of oxygen with inert gas, argon, or nitrogen causes the carbon-oxygen reaction to go to completion in favor of the oxidation reaction of iron and the oxidizable elements, notably chromium in stainless steel. Therefore, superior chromium recoveries from less expensive high-carbon ferrochrome are obtained compared to those of electric arc melting practices. The primary aspect of the AOD process is the shift in the decarburization
thermodynamics that is afforded by blowing with mixtures of oxygen and inert gas as opposed to pure oxygen.

The heat is decarburized in the AOD vessel in stages, during which the inert gas-to-oxygen ratio of the blown gas increases from 1-to-3 to 3-to-1. During the blowing, fluxes are added to the furnace and a slag is prepared. Following the decarburization blow, ferrosilicon is added, and the heat is
argon stirred for a short period. The furnace is then turned down, a chemistry sample is taken, and the heat is deslagged. Additional alloying elements are added if adjustments are necessary, and the heat is tapped into a ladle and poured into ingot molds or a continuous casting machine. With the AOD process, steels with low hydrogen (<2 ppm) and nitrogen (<0.005%) can be produced with complete recovery of chromium. Foundries and integrated steel mills use vessels ranging in nominal capacity from 1 to 160 Mg (1 to 175 tons).

The AOD process for refining stainless steels allows accurate control of the chemistry, in particular, control of carbon and sulfur. Prior to AOD, carbon could not be removed during refining without also removing chromium. Most stainless steels are available with different levels of carbon. For resistance to intergranular corrosion, a low carbon content is preferred, usually a maximum of 0.03 wt% C. Such a stainless steel is referred to as an “L” grade, for example, 304L and 316L. For aqueous corrosion resistance, the lower the carbon content the better the resistance. For high-temperature service, the opposite is true, and some minimum amount of carbon is required for both tensile and creep-rupture strength. Low-carbon grades could only be produced by starting with low-carbon raw materials, specifically low-carbon ferrochrome. The expense of low-carbon ferrochrome meant that the L grades were inherently more expensive. AOD enables reduction of carbon to very low levels, even if the starting stock contains higher carbon.

Using AOD, it is also possible to add a very small, precisely controlled amount of nitrogen. This does not harm intergranular corrosion resistance but increases the room-temperature tensile properties. Like carbon, sulfur can now readily be reduced to very low levels, typically less than 0.005 wt%. Usually, stainless steels intended for plate are refined to a low sulfur level to improve hot workability. Plate is generally formed and welded, usually with little machining by the user. However, low sulfur is quite detrimental to machinability. Because bar products are usually machined, most stainless bar must actually be resulfurized to some level (~0.02 wt%) for improved machinability. Precise control of chemistry, in particular nitrogen, has permitted development of the superaustenitic 6% Mo grades. The ability to closely control nitrogen as an alloying addition has also tremendously improved the weldability of duplex stainless steels.

Although the process was initially targeted for stainless steel production, AOD is used in refining a range of alloys, including stainless steels, tool steels, silicon (electrical) steels, carbon steels, low-alloy steels, high-strength low-alloy steels, and high-temperature alloys and superalloys. Argon oxygen decarburization units are used in the production of high-alloy castings, particularly of grades that are prone to defects due to high gas contents. Carbon and low-alloy steels for castings with heavy wall sections may be subject to hydrogen embrittlement and are also processed in these units with good results.
Ingot Casting

After the ladle refining operations are complete, the liquid steel is cast in molds to produce ingots or continuously cast in a continuous casting machine. Although ingot casting has been the traditional method, continuous casting has rapidly evolved as the method of choice because of cost and quality advantages. During ingot casting, the ladle is moved by an overhead crane so that it can be tapped or teemed into individual upright-standing molds on rail cars. Ingot molds are slightly tapered, as shown in Fig. 13, for easier removal of the ingots after solidification. After stripping from the molds, the hot ingots are transferred to soaking pits where they are reheated for hot rolling.

During solidification, excess gases are expelled from the solidifying metal. Oxygen in the form of FeO reacts with carbon to produce carbon monoxide according to Eq 2. Because steel solidifies over a range of temperatures, gases evolving from the solidifying metal are trapped at the solid-liquid interfaces, producing porosity known as blowholes. The amount of oxygen dissolved in the liquid steel just before casting can be controlled by adding deoxidizing agents such as aluminum or ferrosilicon. Depending on the amount of gases (mainly oxygen) remaining in the liquid steel during the solidification process, the resulting ingot structure is either rimmed, capped, semikilled, or killed, as shown in Fig. 13. The deoxidation method used is based on economics and end use of the steel.

**Rimmed steels** are only slightly deoxidized, so that a large evolution of gas occurs as the metal begins to solidify. The gas is a product of the reaction between the carbon and oxygen in the molten steel, which occurs at the boundary between the solidified metal and the remaining molten metal. As a result, the outer “rim” of the ingot is practically free of carbon. Rimming may be stopped mechanically after a desired period, or it may continue until the rimming action subsides and the top freezes over, thereby ending

![Fig. 13 Types of ingot structures. Source: Ref 1](image-url)
all gas evolution. The center portion of the ingot, which solidifies after the rimming ceases, has a carbon composition somewhat above that of the original molten metal as a result of the segregation tendencies. The low-carbon surface layer of rimmed steel is very ductile. Proper control of the rimming action will result in a very sound surface for subsequent rolling. Consequently, rimmed grades are particularly adaptable to applications involving cold forming and where the surface finish is of prime importance. The presence of an appreciable percentage of carbon or manganese decreases the oxygen available for the rimming action. If the carbon content is greater than 0.25 wt% and the manganese is greater than 0.60 wt%, the action will be very sluggish or nonexistent. If a rim is formed, it will be quite thin and porous. As a result, the cold forming properties and surface quality are seriously impaired. It is therefore standard practice to specify rimmed steel only for grades with low percentages of carbon and manganese. Rimmed steel is cheaper to produce because the top portion of the ingot does not have a large gas cavity that must be scrapped, which means the yield is higher.

**Capped steels** are much the same as rimmed steels except that the duration of the rimming action is curtailed. A deoxidizer is usually added during pouring of the ingot, with the result that a sufficient amount of gas is entrapped in the solidifying steel to cause the metal to occupy a larger volume in the mold. The rising metal contacts the cap, thereby stopping the action. A similar effect can be obtained by adding ferrosilicon or aluminum to the ingot top after the ingot has cooled for the desired time. Rimming times of 1 to 3 min prior to capping are most common. Capped steels have a thin, low-carbon rim that imparts the surface and cold forming characteristics of rimmed steel. The remainder of the cross section approaches the uniformity typical of semikilled steels.

**Semikilled steels** are intermediate in deoxidation between the rimmed and killed grades. Sufficient oxygen is retained so that its evolution counteracts the shrinkage on solidification, but there is no rimming action. Consequently, the composition is more uniform than rimmed steel, but there is also a greater possibility of segregation than in killed steels. Semikilled steels are used where neither the surface nor the cold forming characteristics of rimmed steels nor the greater uniformity of killed steels are essential requirements.

**Killed steels** are strongly deoxidized and characterized by a relatively high degree of uniformity in composition and properties. The metal shrinks during solidification, forming a cavity or pipe in the extreme upper portion of the ingot. Generally, these grades are poured in big-end-up molds. A “hot top” brick is placed on top of the mold before pouring and filled with metal after the ingot is poured. The pipe formed will be confined
to the hot-top section of the ingot, which is removed by cropping before rolling. The most severe segregation of the ingot will also be removed by cropping. While killed steels are more uniform in composition and properties than any other type, they are nevertheless susceptible to some degree of segregation. As in the other grades, the top center portion of the ingot will exhibit greater segregation than the balance of the ingot. The uniformity of killed steel makes it most suitable for applications involving operations such as forging, piercing, carburizing, and heat treatment. Aluminum-killed steels are widely used for cold rolled sheet that will be used for severe forming or deep drawing. These steels exhibit a minimum of strain aging and have a fine grain size.

**Continuous Casting**

Today, most steel is cast into solid form in a continuous casting machine. In the continuous casting process (Fig. 14), the ladle of molten steel is transported to an elevated casting platform above the casting machine. The molten steel is poured into a rectangular trough, called a tundish, which acts as a reservoir for the steel. From a spout in the bottom of the tundish,
the molten steel is poured into a water-cooled mold with a movable temporary bottom. As the molten steel enters the mold, the metal at the surface of the mold solidifies, forming a thin skin. The skin thickens as the metal passes through the mold, and the temporary bottom is slowly lowered to allow metal to be continuously poured into the mold. The remaining metal in the center of the ingot is solidified by spraying cold water onto the ingot as it leaves the mold. The solid metal billet is pulled by rollers so that a long, continuous steel slab is produced. At the end of the machine, it is straightened and cut to the required length. Fully formed slabs, blooms, and billets emerge from the end of this continuous process. The continuous casting process runs for days or weeks as ladle after ladle of molten steel feeds the casting machine.

The advantages of the continuous casting process include reduced costs, improved quality, increased yield, lower energy costs, and less pollution. It is now the process of choice for high-volume, low-cost plain carbon steels. Quality improvements include less variability in chemical composition, both through the thickness and along the length of the continuously cast slab. The surface quality of the slab is also higher than for an ingot, having fewer surface defects such as seams and scabs. The yield for continuous casting is also higher, because it is not necessary to crop the ends of continuously cast slabs. Energy savings are achieved, because the continuously cast slabs are sent directly to rolling mills and do not require soaking pits for reheating. In addition, because the thickness of continuously cast slabs is approximately half the thickness of individual ingots, much less hot rolling is required.

**Rolling**

Rolling is the reduction of the cross-sectional area of the metal stock, or the general shaping of the metal products, through the use of the rotating rolls. The rolls rotate to pull and simultaneously squeeze the work between them. After ingot casting, rolling is perhaps the most important metalworking process. More than 90% of all wrought steel, aluminum, and copper produced go through at least one rolling process. The main advantage of rolling lies in its ability to produce desired shapes from relatively large pieces of metals at very high speeds in a somewhat continuous manner.

Rolling can be carried out hot, warm, or cold, depending on the application and the material involved. Hot rolling helps to break up the as-cast structure, provides a more uniform grain size, and produces a better distribution and size of constituent particles. During rolling, compression deformation is accomplished by using two work rolls. Because the rolls rotate with a surface velocity exceeding the speed of the incoming metal, friction along the contact interface grabs the metal and propels it forward.
The amount of deformation that can be achieved in a single pass between a given pair of rolls depends on the frictional conditions along the interface. If too much deformation is attempted, the rolls will simply skid over stationary metal, while too little deformation per pass results in excessive cost.

Many engineering metals are often cast into ingots and then processed by hot rolling into blooms, billets, and slabs (Fig. 15), which are then rolled into other products, such as plate, sheet, tube, rod, bar, and structural shapes. A bloom is a product of the initial ingot breakdown. Generally, the width of a bloom equals its thickness, and the cross-sectional area is greater than 205 cm$^2$ (32 in.$^2$). Further reduction by hot rolling produces a billet that has a minimum cross section of approximately 38 by 38 mm (1.5 by 1.5 in.). A slab refers to hot rolled ingot with a cross-sectional area greater than 100 cm$^2$ (15 in.$^2$) and with a width that is at least twice the thickness. Blooms, billets, and slabs are known as semifinished products because they are subsequently formed into other mill products.

The difference between plate and sheet is determined by the thickness of the product. In general, plate has a thickness greater than 6.4 mm (0.25 in.), although there are exceptions to this limit, depending on the width. Sheet and strip refer to rolled products that have a thickness less than 6.4 mm. Strip refers to rolled product with widths no greater than 64 mm, while sheet refers to wider material.

Rolling of blooms, slabs, billets, plates, and structural shapes is usually done at temperatures above the recrystallization temperature, where large reductions in height or thickness are possible with moderate forming pressures. Sheet and strip are often cold rolled in order to maintain closer thickness tolerances and provide superior surface finishes.

Fig. 15 Rolling sequences. Source: Ref 14
Types of Rolling Mills

The three principal types of rolling mills are the two-high, three-high, and four-high mills shown in Fig. 16. As their names imply, this classification is based on the way the rolls are arranged in the housings. Two-high mills may be either pull-over mills or reversing mills. In pull-over mills, the rolls run in only one direction. The workpiece must be returned over the top of the mill for further rolling. Reversing mills employ rolls in which the direction of rotation can be reversed. Rolling then takes place alternately in two opposite directions. Reversing mills are among the most widely used in industry and can be used to produce slabs, blooms, plates, billets, rounds, and partially formed sections suitable for rolling into finished shapes on other mills.

In three-high mills, the top and bottom rolls rotate in the same direction, while the middle roll rotates in the opposite direction. This allows the workpiece to be passed back and forth alternately through the top and middle rolls, and then through the bottom and middle rolls without reversing the direction of roll rotation.

Because the roll-work contact length is reduced with a smaller roll radius, leading to lower forces, torque, and power, the four-high rolling mill uses two smaller-diameter rolls to contact the work, with two larger
backing rolls for support. The larger backup rolls reinforce the smaller work rolls, thus allowing fairly large reductions without excessive amounts of roll deflection. Four-high mills are used to produce wide plates and hot rolled or cold rolled sheet, as well as strip of uniform thickness.

Another important type of mill that uses smaller working rolls against the workpiece is the cluster mill, the most common being the Sendzimir mill. In a typical Sendzimir mill design (Fig. 17) each work roll is supported through its entire length by two rolls, which in turn are supported by three rolls. These rolls transfer roll separating forces through four large backup rolls to a rigid cast steel housing. Sendzimir mills are used for the cold rolling of sheet and foil to precise thicknesses. To achieve higher throughput rates in standard products, a tandem rolling mill is often used, consisting of a series of rolling stands. However, with each rolling step, work velocity increases so the rolling speeds at each stand must be synchronized. Hot rolling is also used to produce structural shapes. As shown in the example for an I-beam in Fig. 18, multiple stands are used to gradually produce the desired shape.

Another type of rolling mill design is the planetary mill shown in Fig. 19. This mill consists of a pair of heavy backing rolls surrounded by a large number of small planetary rolls. The chief feature of the planetary roll is that it hot reduces a slab directly into strip in one pass through the mill. Each planetary roll gives an almost constant reduction to the slab as it sweeps out a circular path between the backing roll and the slab. As each pair of planetary rolls ceases to have contact with the workpiece, another

![Fig. 17 Sendzimir mill. Source: Ref 14](image)
Fig. 18 Rolling of an I-beam. Source: Ref 15

Fig. 19 Planetary mill. Source: Ref 14
pair of rolls makes contact and repeats the reduction. The overall reduction is the summation of a series of small reductions by each pair of rolls in turn following each other in rapid succession. The action in the planetary mill is more like forging than rolling. Planetary mills are capable of reductions of up to 98% in a single pass and have been designed up to 203 cm (80 in.) in width.

For high production it is common to install a series of rolling mills one after another in tandem (Fig. 20). Each set of rolls is called a stand.

Fig. 20  (a) Schematic of four-stand mill. (b) Finishing stands of a 2130 mm (84 in.) hot strip mill. Courtesy of Mesta Machine Company. Source: Ref 16
Because a different reduction is taken at each stand, the strip will be moving at different velocities at each stage in the mill. The speed of each set of rolls is synchronized so that each successive stand takes the strip at a speed equal to the delivery speed of the preceding stand. The uncoiler and windup reel not only accomplish the functions of feeding the stock to the rolls and coiling up the final product but can also be used to supply back tension and front tension to the strip.

After hot rolling, many products undergo further processing by cold rolling. Prior to cold rolling, coils of steel are usually annealed to remove any cold work introduced during hot rolling. Cold rolling, usually performed at room temperature, permits the thickness of the strip to be closely controlled while also improving the surface quality. Because cold rolling work hardens the metal, sheet metal that is going to be subsequently used for forming or pressing operations is annealed to soften it. Depending on the particular equipment and cold rolling parameters, different patterns of residual stresses can be produced in cold rolled sheet (Fig. 21). If the product is going to be used in the cold rolled state, it is better to use smaller rollers and/or smaller reductions per pass to produce compressive residual stresses on the surface.

Because the nonferrous metal industry deals with a diverse product mix, the equipment used for hot rolling is usually less specialized than that in the steel industry. The smaller ingot sizes and lower flow stresses for many nonferrous metals permit the use of smaller rolling mills. Two- and three-high mills are used for most hot rolling of nonferrous alloys, although continuous four-high mills are used for aluminum alloys.

**Fig. 21** Residual stress patterns produced by rolling. Source: Ref 15
**Rolls**

Of all the components of a rolling mill, the rolls are of primary interest, because they control the reduction and shaping of the work metal. There are three main parts of a roll: the body (the part on which the actual rolling takes place), the necks (which support the body and take the rolling pressure), and the driving ends, commonly known as wobblers (where the driving force is applied). These parts are shown in Fig. 22.

Rolls must have good wear resistance; sufficient strength to withstand the bending, torsional, and shearing stresses to which they are subjected; and, for hot rolling, ability to withstand elevated temperatures without heat checking (thermal fatigue) and oxidation. Rolls are normally constructed of cast iron, cast steel, and forged and hardened steel, depending on the rolling application and the material being rolled.

**Defects In Rolling**

A number of defects or undesirable conditions can develop in the rolling of flat, bar, or shaped products. Very broadly, these problems can be attributed to one of four sources: melting and casting practice, metallurgical sources, heating practice, and rolling practice.

**Melting and Casting Practice.** The major problems associated with melting and casting practice are the development of porosity and a condition known as scabs. Porosity is developed in cast ingots when they solidify and is of two types: pipe and blow holes. Pipe is a concave cavity formed at the top of the ingot due to nonuniform cooling and shrinkage. If not cropped off, pipe can be rolled into the final product to form an internal lamination (Fig. 23). These laminations may not be immediately evident following rolling but may become apparent during a subsequent forming operation. The occurrence of laminations is most prevalent in flat rolled sheet products. Blow holes are usually a less serious defect. They are the result of gas bubbles entrapped in the metal as the ingot solidifies. If the surfaces of holes are not oxidized, they may be welded closed during the rolling operation.

Scabs are caused by improper ingot pouring, in which metal is splashed against the side of the mold wall. The splashed material, or scab, tends to stick to the wall and become oxidized. Scabs usually show up only after rolling and, as can be expected, give poor surface finish.

![Fig. 22](image)

**Fig. 22** Principal parts of a rolling mill roll. Source: Ref 14
Metallurgical Sources. Defects such as poor surface finish may also result from metallurgical source nonmetallic inclusions. In steels, inclusions are of two types, refractory and plastic. Refractory inclusions are often metallic oxides such as alumina in aluminum-killed steels or complex oxides of manganese and iron in rimmed steels. When near the surface, these inclusions give rise to defects known as seams and slivers (Fig. 24).

Plastic inclusions, such as manganese sulfides, elongate in the rolling direction during hot forming. The presence of these elongated inclusions

Fig. 23 Laminations in rolled steel sheet resulting from insufficient cropping of the pipe from the top of a conventionally cast ingot. Courtesy of V. Demski, Teledyne Rodney Metals. Source: Ref 14

Fig. 24 (a) Seams and (b) slivers caused in rolled material by the presence of surface inclusions. Courtesy of V. Demski, Teledyne Rodney Metals. Source: Ref 14
(stringers) produces fibering, which causes directional properties. For example, ductility transverse to the fiber is frequently lower than parallel to it. In high-strength, low-alloy steels, sulfide shape-control elements, such as cerium, are often added to prevent the development of such fibering, which is especially undesirable from the viewpoint of subsequent forming operations or service behavior.

Another rolling defect whose source is metallurgical is alligatoring (Fig. 25). This defect, found most frequently in rolled slabs of aluminum-magnesium, zinc, and copper-base alloys, is manifested by a gross midplane fracture at the leading edges of the rolled metal.

**Heating Practice.** Two rolling defects that stem from heating practice are rolled-in scale and blisters. The development of scale during preheating of ingots, slabs, or blooms is almost inevitable, particularly for steels. Sometimes descaling operations involving hydraulic sprays or preliminary light rolling passes are not totally successful; scale may get rolled into the metal surface and become elongated into streaks during subsequent rolling. The other defect, blistering, is a raised spot on the surface caused by expansion of subsurface gas during heating. Blisters may break open during rolling and produce a defect that looks like a gouge or surface lamination.

**Rolling practice** can also cause defects. For example, in bar and shape rolling, excessive reduction in the finishing pass may cause metal to extrude laterally in the roll gap, leading to a defect known as finning. Finning in an intermediate pass causes folds or laps in subsequent passes. Excessive reduction in the leader pass (the pass prior to the finishing pass) may also wrinkle open the sides of a bar, which after turning 90° in the finishing pass can result in a series of hairline cracks.

![Fig. 25 Alligatoring in a rolled slab. This defect is thought to be caused by nonhomogeneous deformation and nonuniform recrystallization during primary rolling of such metals as zinc alloys, aluminum-magnesium alloys, and copper-base alloys. Courtesy of J. Schey, University of Waterloo. Source: Ref 14](Image)
In the rolling of slabs and plates, two defects that affect yield are fishtail and overlaps, both of which need to be trimmed off (Fig. 26). Fishtailing results from nonuniform reduction in the width, and overlapping results from nonuniform reduction in thickness. These defects can be reduced by proper design of the blooming and rolling sequence. Several defects, such as wavy edges, center buckle, herringbone, and quarter buckle can be created in cold rolling of sheets and strips. These defects are primarily due to localized overrolling, which can occur because of improper roll profiles or variations in the properties or shape of the incoming strip.

**Rolling of Steels**

After continuous casting and inspection, followed by slab reheating in the reheat furnace (if necessary), the slab is prepared for the roughing and tandem 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; coatings include zinc, tin, zincozalume, paint, enamel, and so on. Slabs cut from the continuous casting machine are reheated to bring the steel to approximately 1200 °C (2190 °F).

**Hot Rolling of Steels**

Hot rolling is carried out with the steel in its γ, or austenite phase. The steel is plastic and particularly malleable at temperatures that range from 1200 °C (2150 °F) to as low as 800 °C (1470 °F). This allows large reductions in thickness, for example, from 250 mm (10 in.) thick slab to 2 mm (0.1 in.) thick hot strip with relatively small force. Following hot rolling, the steel transforms into its low-temperature α, or ferrite, phase (plus other

*Fig. 26* Overlap and fishtail formed during rolling of slabs and plates. Overlap is the result of nonuniform deformation in thickness, while fishtail is caused by nonuniform deformation in width. Source: Ref 14
constituents) on cooling. The characteristics of this transformation, which has a significant effect on the mechanical properties of the product, depend on the cooling rates used on the runout cooling tables.

Semifinished blooms, billets, and slabs are transported from the steel-making plant to the rolling mills. Steel products are classified into two basic types according to their shape: flat products and long products. Slabs are used to roll flat products, while blooms and billets are mostly used to roll long products. Billets are smaller than blooms and therefore are used for smaller long products. Semifinished products are heated until they are red hot (~1200 °C, or 2200 °F) and passed through a roughing stand, a collection of steel rolls that squeeze the hot steel into the required shape. The steel is passed backward and forward through the roughing stands several times, with each pass approaching the shape and dimension of the finished product.

**Plate Mills.** Slabs are used to make plate—large, flat pieces of steel in the range of 6 to 51 mm (0.25 to 2.00 in.) thick and up to 5 m (15 ft) wide. After leaving the plate mill roughing stand, they are passed through a finishing stand, a reversing mill where the steel is passed backward and forward through the mill. It is usually rotated 90° and rolled sideways at one stage during the process.

**Strip Mills.** Slabs are also used to make steel strip, called hot rolled coil. After leaving the roughing stand, the slab passes continuously through a series of finishing stands (Fig. 20b) that progressively reduce the thickness. As the steel becomes thinner, it also becomes longer and moves through the rolls faster. Because different parts of the same piece of steel are traveling at different speeds through the different rolls, this process requires very close computer control of the speeds at each individual stand of rolls. By the time it reaches the end of the mill, the steel can be traveling at speeds approaching 64 km/h (40 mph). As the long strip of steel comes off the strip mill, it is coiled and allowed to cool. Hot rolled strip frequently goes through further stages of processing, such as cold rolling.

**Long Product Mills.** Long products are so called because they come off the mill as long bars of steel. They are produced in a vast range of shapes and sizes with cross sections shaped like an H, I, U, or a T. Bars can have cross sections in the shape of squares, rectangles, circles, hexagons, and angles. Rod is coiled and drawn into wire or fabricated into products used to reinforce concrete buildings. Other types of long product include railway rails and piling. Blooms and billets are used to make long products. After leaving the roughing stand, the steel passes through a succession of stands that reduces their size and changes their shape. In a universal mill, all faces are rolled at the same time. In other mills, only two sides of the
steel are rolled at any one time, the piece of steel being turned over to allow the other two sides to be rolled.

**Cooling Beds and Runout Tables.** Following hot rolling, the steel is generally cooled down to room temperature. For plates and bars this is carried out on cooling beds. For strip it is carried out on runout tables and during holding, which follows coiling. For rods it is carried out in water boxes and along cooling lines employing large volumes of forced air. Except for certain grades of stainless and electrical steels, the cooling always involves the transformation of austenite into ferrite, as well as into a number of other transformation products, such as pearlite, bainite, and martensite. The particular transformation product that forms, as well as its general characteristics, depends on the cooling rate that is achieved. The faster the cooling rate within a given product range, the stronger the microstructure that is produced. As a result, there is considerable interest in the use of accelerated cooling to promote the formation of appropriate microstructures. In fact, for most steel products, this process is the least expensive way to increase the strength.

**Cold Rolling and Annealing of Steels**

About half of all rolled steel products are sold in the as-hot-rolled condition. This includes items such as rails and structural sections (I beams, channels, angles, and so on), and plates and seamless tubes, as well as certain relatively thick grades of sheet and strip that are employed in the as-rolled condition; for example, for the forming of bumpers and car wheels, or for the manufacture of pipe. Nevertheless, numerous products require much more reduction in thickness or cross section and considerably better surface quality than can be produced by hot rolling; this is where cold rolling plays a role. Although cold rolling does not alter the shape, it does reduce the thickness and workhardens the steel. During cold rolling, the previously hot rolled strip is uncoiled and passed through a series of rolling mill stands that progressively reduce its thickness. The cold rolled strip is then recoiled. Because the cold rolling process produces a hard sheet with little ductility, it is usually annealed by either continuous or batch annealing.

Cold rolling increases the hardness and yield strength, reduces the ductility and formability, and also introduces the specific texture components associated with thickness reduction at a constant width (known as plane-strain deformation) that can be later enhanced by annealing. Some products are sold and used in such a strengthened condition, particularly when little further deformation or shaping is involved. However, when appreciable further forming operations are required, such as in the manufacture of cans or the deep drawing of auto body parts, annealing must follow cold rolling. Annealing removes the work hardening introduced by rolling and
thus restores the formability of the material. When employed after the appropriate processing of selected grades, for example, aluminum-killed drawing-quality (AKDQ) or interstitial-free (IF) steels, annealing also brings about an increase in the normal anisotropy, which leads to significant further increases in deep drawability.

**Batch annealing** traditionally has been used to anneal coiled rolls of cold rolled steel. However, much faster continuous annealing lines are now being used. A comparison of heating profiles for the two processes is shown in Fig. 27. The most common method of batch annealing cold rolled sheet is by box annealing, in which coils of steel are stacked three or four high and placed under a cover (Fig. 28). They are then heated to approximately 590 to 760 °C (1100 to 1400 °F) in a reducing atmosphere to prevent decarburization. Very slow heat-up and cool-down rates are associated with batch annealing, resulting in a coarse pearlitic structure. Because almost all of the carbon in the steel is precipitated as pearlite, steel produced in this manner normally has a low susceptibility to strain aging. Batch annealing is slow, requiring several days.

**Continuous Annealing.** A much faster process that is increasingly used is continuous annealing. The steel sheet is uncoiled and rapidly passed through high-temperature zones in continuous annealing furnaces. An integrated continuous cold rolling and annealing line is depicted in Fig. 29. Continuous annealing requires only minutes to recrystallize a section of

![Fig. 27 Batch and continuous annealing cycles. Source: Ref 17](image-url)
sheet as it passes through the hot zone of a furnace. However, because the heat-up and cool-down rates are much faster, various cooling profiles, called overaging, must be used to remove carbon and nitrogen from the solution and reduce the susceptibility to strain aging. Generally, the rapid anneal cycle of a continuous anneal process results in material properties that are less ductile than those resulting from a box anneal cycle. However, continuous annealing results in more uniformity of properties throughout the length of a coil.

Most cold rolled steels are subcritically annealed; that is, they are annealed below the $A_1$ temperature (Fig. 27). However, continuous annealing lines have made possible intercritical heating into the ferrite-austenite

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**Fig. 28** Three methods of batch annealing. Source: Ref 18

**Fig. 29** Integrated cold rolling and annealing line. Source: Ref 18
field, with cooling that is rapid enough to cause the austenite to transform to martensite. As a result, early yielding is continuous and occurs with high rates of strain hardening. Intercritically annealed steels with ferrite-martensite microstructures are referred to as dual-phase steels that have strength levels in the 345 to 550 MPa (50 to 80 ksi) range.

Rimmed or capped ingot cast steel (Fig. 15) traditionally has been used because of its lower price. However, rimmed and capped steels are susceptible to quench and strain aging. Strain aging and quench aging can produce localized deformation and discontinuous yielding. This causes stretcher strains during forming and unacceptable surface finishes on formed parts. To eliminate stretcher strains, cold rolled and annealed sheet steels are temper rolled. Temper rolling introduces just enough strain so that the deformed sheet will strain uniformly or continuously. However, the yield point will reappear with time. Where strain aging is to be avoided and/or when exceptional formability is required, steel killed with aluminum is preferred, because nitrogen, a primary contributor to strain aging, is tied up as inert aluminum nitride (AlN) particles. In addition, all continuously cast steel must be fully killed to allow casting.

Another form of cold working is cold drawing. Metal in rod form is drawn through a series of dies that progressively reduce the rod circumference to produce wire. The drawing process substantially increases the material tensile strength. Drawn wires can be spun into huge cables for suspension bridges that have very high strengths.

Aluminum Production

To produce pure aluminum, alumina (Al₂O₃) is first extracted from the mineral bauxite, which contains approximately 50% Al₂O₃. In the Bayer process, a sodium hydroxide solution is used to precipitate aluminum hydroxide, which is then calcined to form alumina. Alumina is then converted to pure aluminum by electrolysis, using the Hall-Héroult process, illustrated in Fig. 30. The cell is lined with carbon cathodes, and consumable electrodes are gradually fed into the top of the cell. The electrolyte is cryolite (Na₃AlF₆) with 8 to 10 wt% Al₂O₃ dissolved in it. The cell operates at temperatures in the range of 955 to 1010 °C (1750 to 1850 °F), with a power rating of 10 to 12 kW·h/kg aluminum. Pure aluminum (99 wt%) is reduced at the cathode and forms a molten pool in the bottom of the cell, which is drained from the bottom and cast into aluminum ingots. Because impurities, such as iron and silicon, are reduced along with the aluminum, the raw materials used in the Bayer process are carefully controlled to minimize these metal oxides. Because the production of aluminum takes a lot of electrical energy, and recycling aluminum takes much less energy, a large portion of general-purpose aluminum currently is made from recycled material.
During the casting of aluminum alloy ingots, oxides and gases must be controlled. Aluminum oxidizes rapidly in the liquid state and reverts back to alumina. Once the oxide becomes entrapped in the liquid metal, it is difficult to remove and remains dispersed in the liquid metal. The main source of oxygen is moisture from the furnace charge. Oxides are removed by fluxing with gases, solids, or molten salts. Various filtration methods are also used to remove oxides during pouring. Hydrogen is the only gas with appreciable solubility in molten aluminum and can cause blisters in heat treated parts and porosity in aluminum castings. Again, moisture from the furnace charge is the main source of hydrogen. Hydrogen can also be introduced from moisture in the air and products of combustion. Hydrogen is removed by bubbling chlorine, nitrogen, or argon gas through the melt.

The semicontinuous direct-chill process is the mostly widely used process for casting commercial ingots that will receive further processing, such as rolling, extrusion, or forging. It produces fine-grained ingots at high production rates. As shown in Fig. 31, the molten aluminum is poured into a shallow, water-cooled mold of the required shape. When the metal begins to freeze, the false bottom in the mold is lowered at a controlled rate, and water is sprayed on the freshly solidified metal as it exits the mold. A water box or spray rings are placed around the ingot to rapidly cool the ingot. Metals with low melting points, such as magnesium, copper, and zinc, are added directly to the molten charge, while high-melting-point elements (e.g., titanium, chromium, zirconium, and manganese) are added as master alloys. Inoculants, such as titanium and titanium-boron, are added to reduce hot cracking and refine grain size.

Fig. 30 Electrolytic cell used to produce aluminum. Courtesy of Alcoa, Inc. Source: Ref 18
One of the main advantages of direct-chill continuous casting is that it helps to eliminate the segregation that occurs in high-strength alloys produced by the older tilt-casting procedures. These alloys, when produced by tilt casting, are highly segregated because of the broad solidification temperature ranges and the shape of the freezing front. Direct-chill casting eliminates most of this type of segregation because the liquid metal freezing front is almost horizontal, and the liquid metal freezes from the bottom to the top of the ingot. During direct-chill casting, the pouring temperature is maintained at only approximately 28 °C (80 °F) above the liquidus temperature; this helps reduce oxide formation and hydrogen pickup and produces a fine-grained structure. It can also produce fairly large ingots at slow speeds, a necessary requirement for the high-strength alloys to...

**Fig. 31** Semicontinuous direct-chill casting. Source: Ref 19
prevent cracking. Typical casting speeds are in the range of 2.5 to 13 cm/min (1 to 5 in./min).

**Rolling Aluminum Plate and Sheet**

Rolled aluminum is the most common of the wrought aluminum product forms. Aluminum plate, sheet, and foil are produced from aluminum ingots using the following steps:

1. Scalping of the ingot
2. Preheating and homogenizing the ingot
3. Reheating the ingot, if required, to the hot rolling temperature
4. Hot rolling to form a slab
5. Intermediate annealing
6. Cold rolling along with intermediate anneals to form sheet and foil product forms

**Scalping of Ingots.** To prevent surface defects on the cast ingot from being rolled into the surface, approximately 6.3 to 9.5 mm (0.250 to 0.375 in.) are removed from the surfaces to be rolled. Some alloys, such as 1100, 3003, and 3015, have fairly smooth as-cast surfaces and do not require scalping. Other, more highly alloyed ingots, such as magnesium-containing alloys and high-strength aircraft alloys, are always scalped.

**Preheating or homogenizing** puts into solid solution all the constituents that are soluble and reduces the coring that occurs during the casting process. It relieves stresses in the ingot and makes the cast structure more uniform and more readily hot worked. Soaking temperatures and times depend on the specific alloy. For example, 1100 aluminum is soaked for approximately 1 h at 455 to 510 °C (850 to 950 °F), while 7075 requires up to 24 h at 455 to 470 °C (850 to 875 °F). Ingots that are going to be clad during hot rolling are scalped after preheating to avoid the heavy oxidation that occurs during the long preheating cycle. This allows the cladding to form a better bond during hot rolling.

**Hot rolling** conducted above the recrystallization temperature produces a fine grain structure and a minimum of grain directionality. The upper limit is set by the lowest-melting-point eutectic present in the alloy, while the lower temperature is the temperature at which the metal is hot enough to be sufficiently reduced with each pass through the mill without cracking.

The ingot is removed from the soaking pit and initially put through a series of four-high rolling mills to break down the ingot structure. Breakdown temperatures are in the range of 400 to 540 °C (750 to 1000 °F), with continuous rolling temperatures of approximately 290 to 455 °C (550
to 850 °F). Because the work rapidly lengthens in the direction of rolling, it is necessary to remove the slab from the mill, turn it around, and then cross roll it to produce wide sheet or plate. The grain structure becomes elongated in the rolling direction, as shown in Fig. 32. This results in anistropic mechanical properties in which the properties are lowest in the through-the-thickness (short-transverse) direction. Rolling into thinner plate and sheet is then conducted on five-stand four-high mills, with successive reductions at each mill. Aluminum sheet stock, which can exit the last mill at speeds approaching 485 km/h (300 mph), is coiled into large coils prior to cold rolling.

**Intermediate Annealing.** Because hot rolling produces some cold work, coiled aluminum sheet stock is given an intermediate anneal prior to cold rolling. Because the amount of cold work introduced during cold

![Fig. 32](image)

*Fig. 32* Grain directionality due to rolling. Source: Ref 20
Cold Rolling. Sheet and foil are cold rolled after hot rolling to produce a much better surface finish and control the strength and ductility through work hardening. Again, four-high mills are used along with lubricants and, if a bright surface finish is required, polished rolls. Depending on the amount of reduction and the final strength required, intermediate anneals are conducted during the cold rolling process. Normally, reductions in the range of 45 to 85% are taken between anneals.

Titanium Production

Titanium for ingot production may be either titanium sponge or reclaimed scrap (revert). In both cases, stringent specifications must be met for control of ingot composition. Most important are the hard, brittle, and refractory titanium oxide, titanium nitride, or complex titanium oxynitride particles that, if retained through subsequent melting operations, could act as crack initiation sites, especially during fatigue loading.

Titanium sponge is manufactured by first chlorinating rutile ore and reducing the resulting TiCl₄ with either sodium (Hunter process) or magnesium (Kroll process) metal. Sodium-reduced sponge is leached with acid to remove the NaCl by-product of reduction. Magnesium-reduced sponge may be leached, inert gas swept, or vacuum distilled to remove the excess MgCl₂ by-product. Vacuum distilling results in lower residual levels of magnesium, hydrogen, and chlorine. Modern melting techniques remove volatile substances from sponge, so that high-quality ingot can be produced regardless of which method is used for production of sponge. Revert makes production of ingot titanium more economical than production solely from sponge. If properly controlled, revert is fully acceptable and can be used even in materials for critical structural applications.

Titanium Melting

Titanium sponge, revert, and alloy additions are welded together to form an electrode and then vacuum arc melted (VAR). Ingots from the first melt are then used as the consumable electrodes for second-stage melting. Double melting is used for all applications to ensure an acceptable degree of homogeneity in the resulting product. Triple melting can be used to achieve better uniformity. Triple melting also reduces oxygen-rich or nitrogen-rich inclusions in the microstructure to very low levels by providing an additional melting operation to dissolve them. All melting operations must be done under vacuum to eliminate the introduction of oxygen, nitrogen, and hydrogen. Ingots are normally 650 to 900 mm (26 to 36 in.) in diameter and weigh 3600 to 9000 kg (8000 to 20,000 lb).
Titanium Primary Fabrication

Titanium alloys are available in most mill product forms: billet, bar, plate, sheet, strip, foil, extrusions, wire, and tubing; however, not all alloys are available in all product forms. The product flow for various titanium product forms is shown in Fig. 33. The wrought product forms of titanium and titanium alloys, which include forgings and the typical mill products, constitute more than 70 wt% of the market in titanium and titanium alloy production. Primary fabrication includes the operations performed at the mill to convert ingot into products. Besides producing these shapes, primary fabrication hot working is used to refine the grain size, produce a uniform microstructure, and reduce segregation. It has long been recognized that these initial hot working operations will significantly affect the properties of the final product.

Fig. 33 Titanium product flow. Source: Ref 18
As opposed to steel and aluminum ingots, hot rolling is not used for initial ingot breakdown. Instead, as shown in Fig. 33, hot forging operations are used to breakdown the ingot structure. Prior to thermomechanical processing, the as-cast ingot is conditioned by grinding to remove surface defects. The first step in deforming as-cast ingots is a series of slow-speed steps including upset forging, side pressing, and press cogging to help homogenize the structure and break up the transformed β structure. The ingot is electrically preheated and forged at 925 to 1175 °C (1700 to 2150 °F) in large hydraulic presses so that the deformation can be applied slowly to avoid cracking. These operations are initially done above the β transus but significant amounts of deformation are also done below the β transus, but high in the α + β field, to further refine the microstructure to a fine equiaxed α-β structure while avoiding surface rupturing. With modern processing techniques, billet and forged sections readily meet specified tensile properties prior to final forging.

ACKNOWLEDGMENT


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