Steel Processing Technology

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OVER THE LAST THIRTY YEARS, remarkable advances have been made in the technology of steel processing operations. The first half of this article describes current ironmaking and steelmaking practices (melt, or liquid processing) and discusses the evolution of these processes and their effects on steel properties. The second half of this article describes solid processing of steel, with emphasis on rolling, thermomechanical processing, and annealing of flat steel products. Additional information on the processing of steel can be found in the references provided in this article as well as in the articles that follow in this Section.

Liquid Processing of Steel

The physical chemistry of steelmaking may appear deceptively simple for integrated steel mill operations where ore from the ground is converted into steel. The central reaction merely involves the reduction of iron oxide by carbon:

\[
\begin{align*}
1600 \degree C \\
(2910 \degree F) \\
\text{Fe}_2\text{O}_3 \text{ (iron oxide)} + 2\text{C} \text{ (carbon)} & \rightarrow 2\text{Fe} \text{ (molten iron)} + \text{CO}_2 \text{ (gaseous)} \\
& + \text{CO}_2 \text{ (gaseous)} (\text{Eq} \ 1)
\end{align*}
\]

The final reduction of oxides to liquid iron requires high temperatures of the order of 1600 \degree C (2910 \degree F), to overcome the chemical barrier to oxide reductions and the physical, or thermal, barrier of fusing iron. However, to yield a final steel product with the correct chemistry, quality, and property characteristics, the series of processes depicted in Fig. 1 is typically required.

Ironmaking

The first step in processing liquid iron into high-quality steel involves ironmaking blast furnace, which has evolved over the centuries to become an efficient counter-current exchanger of heat and of mass, or oxygen (Fig. 2). Iron oxide (in pellet or sinter form), coke, and limestone are successively charged through the top of the furnace. The charge slowly descends through the shaft (an 8-h journey) and is gradually heated by hot ascending gases (CO, CO₂, N₂, H₂, H₂O) with a transit time of about 3 s. Because the gas that is lower in the furnace is richer in carbon monoxide, it has a more reducing effect on iron oxides. Thus, the pellets are gradually reduced as a result of mass transfer of carbon monoxide (and hydrogen) from the gas phase into the pellet:

\[
\begin{align*}
\text{3Fe}_2\text{O}_3 & + \text{CO} \rightarrow 2\text{Fe}_3\text{O}_4 + \text{CO}_2 \\
& \text{ (hematite)} \\
\text{Fe}_3\text{O}_4 & + \text{CO} \rightarrow 3\text{FeO} + \text{CO}_2 \\
& \text{ (magnesite)} \\
& \text{ (wustite)} (\text{Eq} \ 2)
\end{align*}
\]

Final deoxidation is accomplished down in the cohesive zone (Fig. 2), where high temperatures and highly reducing conditions result in the reduction of wustite (FeO) to iron. Impurities such as silica, sulfur, alumina, and magnesia, which are present in the original pellets and coke, associate with the lime/ dolomite and are removed as a molten slag. To ensure that this slag is fluid, a composition of about 40% SiO₂, 50% CaO (+MgO) and 10% Al₂O₃ is desired, thereby placing it within the temperature valley, or well, of a ternary eutectic region. The final reduction of the charged pellets, ore, or sinter takes place either by:

\[
\begin{align*}
\text{FeO} + \text{CO} & \rightarrow \text{Fe} + \text{CO}_2 \\
& \text{ (Eq} \ 4)
\end{align*}
\]

or

\[
\begin{align*}
\text{CO}_2 + \text{C} \text{ (coke)} & \rightarrow 2\text{CO} \\
& \text{ (Eq} \ 5)
\end{align*}
\]

The reaction in Eq 4 is termed indirect reduction because the iron oxide is reduced through the intervention of a gaseous reductant. The reaction in Eq 5 is termed direct reduction because the direct contact of wustite with coke leads to droplets of iron that fall through the dripping zone into the hearth.

The CO₂ of Eq 4 reacts immediately with the carbon of the hot coke to form more CO as follows:

\[
\text{CO}_2 + \text{C} \text{ (coke)} \rightarrow 2\text{CO}
\]

This CO₂/CO reaction is often termed the solution loss reaction because it involves the dissolution of coke by CO₂.

Although the obvious purpose of a coke layer is to act as a reductant, the descending coke also plays another critical role. Part of the coke (known as the dead man) forms a supporting pillar for the overlying burden (the ratio of iron and flux to coke and other fuels in the charge). In the region below the cohesive, or sticky, zone (Fig. 2), the remainder of the charge either is molten or is melting (that is, it is composed of slag and pig iron). The final role of the coke is to burn with hot air entering the coke raceways through the tuyeres, thereby generating the high-temperature heat needed for smelting.

Cokemaking. The production of coke required for the tasks described above is also a formidable, capital-intensive operation. The process involves the destructive distillation of metallurgical-grade coals in the coking chambers of the by-product coke ovens. The heat that is needed to distill the volatiles is transferred through the brickwork from adjacent vertical flues by combustion of enriched blast furnace off-gases. After an induction time of approximately 17 h, the incandescent coke is pushed out of the slot ovens into transfer railway cars. During its fall the column of coke breaks apart, forming large lumps that are then transferred to the quenching tower, where an intense and normally intermittent water spray quenches them for subsequent charging into the blast furnace. Retained moisture is kept to a minimum because of the endothermic character of the moisture and consequent thermal load in the blast furnace.

Blast Furnace Stove Use. To achieve overall thermal efficiency, and to generate the high temperatures required for the reduction to iron in the hearth region of the blast furnace, the incoming blast air is preheated to about 1000 \degree C (1830 \degree F) prior to its entry through the water-cooled copper tuyeres. This is accomplished by passing the cold-air blast through a stacked vertical column of preheated (hot) bricks in one of three blast furnace stoves. Because the cold air gradually extracts the stored heat, a separate heating phase is also necessary. This is effected by shutting off the cold-air blast to the stove, opening up the gas valve, and burning enriched blast furnace off-gas...
Ironmaking
Hot metal from blast furnace
Fe + (C, N, P, Si, Mn, S...) →

Hot Metal Desulfurization
De-(S, P, Si) →
Torpedo car

Steelmaking
First-stage refining
De-(C, P, S, Si) →
Deslag (>95%)

Second-stage refining
De-(O, H, N) (RH)
Temperature up (ladle furnace)
Inclusions, alloying (strong stir)

Third-stage refining
De-(O, Cl) →
Shape control of inclusions

Blast furnace
CaC2, CaO, Mg, Na2O, ...

Basic oxygen furnace (or Sumitomo top and blowing process)
CO2/O2

RH vacuum degassing
Vacuum

Ladle furnace
CaO + FeO

Continuous casting
CaO + Ar or CaB2

Injection refining
Vacuum

Snorkel

Continuous casting

Strong stir

Continuous casting

Fig. 1 Major steps in processing liquid iron into high-quality steels. RH, Ruhrstahl Hereaus process

(cleaned with water scrubbers, and electrostatic precipitators) to bring the cooled checkerwork of bricks back up to temperature. Because higher preheat temperatures translate directly into lower coke rates per net tonne of hot metal (NTHM), this heating and cooling cycle requires careful optimization.

Current Blast Furnace Technology. Over the years, significant improvements in burden preparation (such as the development of uniformly sized pellets) and burden lay-
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to remove sulfur from the iron. The reactions taking place can be written as:

\[ \text{CaO (lime)} + (\text{Si})_{\text{Fe}} \rightarrow \text{CaS} + (\text{O})_{\text{Fe}} \]  
\[ \text{CaC}_{2} \text{ (calcium carbide)} + (\text{Si})_{\text{Fe}} \rightarrow \text{CaS} + 2(\text{C})_{\text{Fe}} \]  
\[ (\text{Mg})_{\text{Fe}} + (\text{Si})_{\text{Fe}} \rightarrow \text{MgS} \]

Enhanced desulfurization can be carried out in a blast furnace by using increased slag volumes to absorb the sulfur, but this method requires higher coke rates. Therefore, such practices were abandoned in the 1960s in favor of desulfurization external to the blast furnace.

It is important to remember that calcium and magnesium oxides are much more stable than their sulfide counterparts, calcium sulfide and magnesium sulfate. Consequently, these desulfurizing operations are only effective if dissolved oxygen levels within the iron are low. The presence of iron saturated with carbon ensures this condition; the fundamental interrelation between dissolved carbon and dissolved oxygen in high-carbon molten iron is (Ref 2):

\[ \text{C} + \text{O} \rightarrow \text{CO (gas)} \]
\[ K_{\text{equilibrium}} = \frac{P_{\text{CO}} \text{ (atm)}}{w\% \text{ C wt}\% \text{ O}} = 660 \]

where \( K_{\text{equilibrium}} \) is the thermodynamic equilibrium constant for Eq 10.

The insertion of \( w\% \text{(C)}_{\text{Fe}} = 4.4 \) wt% for hot metal would show \( w\% \text{(O)}_{\text{Fe}} \sim 3 \) ppm for \( P_{\text{CO}} \) at atmospheric pressure if equilibrium applies. It is for this reason that desulfurization is so effective in hot metal. Calcia-rich slags have very high sulfur partition ratios with iron (~400). By contrast, sulfur partitioning in the steelmaking step is at best about 4 to 1 between a basic oxygen furnace (BOF) slag and oxygen-rich steel. Consequently, as much as possible of the sulfur-rich product that floats on the hot metal needs to be scraped or slagged off to prevent the sulfur from reverting to the metal during subsequent (low-carbon) steelmaking steps.

Current Hot-Metal Desulfurization Technology. The well-advanced process technology for desulfurization generally involves the submerged pneumatic injection of, for example, calcium carbide powder that is carried by nitrogen through a deeply submerged refractory-coated steel pipe of about 25 mm (1-in.) inside diameter into hot metal contained within the torpedo car. This vessel (Fig. 1) is customarily used to transport hot metal from the ironmaking facilities to steelmaking operations downstream. Typical industrial practices reduce residual sulfur levels down to 0.01% to 0.02% (S)_{Fe}. The desulfurized hot metal usually is transported in the torpedo car from the blast furnace to the steelmaking shop, where it is emptied into the transfer ladle. As mentioned, any slag carryover

Fig. 2 Principal zones and component parts of an iron blast furnace. Source: Ref 1

ceraming techniques have enhanced the kinetic efficiency of gas/solid and heat/mass transfer interactions. Higher air blast preheat temperatures and improved coke properties have also helped to reduce coke requirements from about 910 kg (2000 lb) per NTHM in the 1950s to current levels of 455 kg (1000 lb) per NTHM.

The iron that is tapped from the blast furnace is saturated with about 4.4% or 22 at.% C. It also contains other impurities that have been reduced from the oxides contained within the iron ore charge. Consequently, the hot metal also contains about 0.3 to 1.3 wt% (Si)_{Fe}, 0.5 to 2 wt% (Mn)_{Fe}, 0.1 to 1.0 wt% (P)_{Fe} and 0.02 to 0.08 wt% (S)_{Fe}. The dissolved sulfur is largely derived from sulfur contained in the coking coal. Dissolved nitrogen levels of the order of 100 ppm would be typical from the air blast. To meet the stringent requirements for high-quality steels, these impurities [(C, S, N, P, ...)]_{Fe} must be brought to very low residual levels using the sequence of operations described below.

Hot Metal Desulfurization

Hot metal from the blast furnace is usually treated with lime, calcium carbide, magnesium, or mixtures of these substances
into the hot metal transfer ladle needs to be removed prior to charging hot metal into the BOF in order to prevent sulfur reversion.

Japanese manufacturers can produce steels with residual hot metal levels of 1 to 2% P; they achieve dephosphorization ahead of the steelmaking step by using injections of sodium carbonate. Because strong compound-forming tendencies exist between phosphorus and sodium, as they do for sulfur and sodium, simultaneous desulfurization and dephosphorization is possible, provided the hot metal has first been desilicized.

**Steelmaking**

*First-Stage Refining.* Because the blast furnace has produced hot metal saturated with carbon and containing other elements, the next operation requires that these impurities (particularly phosphorus) be removed to the required degree. Integrated steel plants normally rely on pneumatically blown oxygen vessels to accomplish these reactions. In a typical BOF, high-velocity (supersonic) jets of pure oxygen are blown onto the hot metal (Fig. 3). Dissolved carbon is oxidized and escapes as carbon monoxide (primarily) and carbon dioxide from the mouth of the vessel, while the other oxidized impurities (Si, Mn, P) enter the slag by fluxing with additions of burnt lime (CaO).

To compensate for the vast amounts of heat liberated during these oxidation reactions, about 30% of the total charge to the furnace comprises steel scrap as coolant. The scrap coolant is required to prevent the temperature of the molten steel from exceeding 1650 °C (3000 °F) and thereby causing unnecessary refractory erosion. Once again, highly complex heat, mass, and fluid transport mechanisms are involved. For example, mass transfer of bath carbon to the scrap metal surfaces effectively dissolves light-section scrap, even though bath temperatures are well below the melting point of the scrap (1500 °C, or 2730 °F) during the major portion of a blow (Fig. 4). Once the bath temperature exceeds the scrap melting range (1500 to 1540 °C, or 2730 to 2800 °F), normal thermal processes that involve turbulent heat transfer will melt the scrap, which finally becomes assimilated into the molten bath. The removal of dissolved carbon as gas and the removal of dissolved silicon, manganese, and phosphorus to an upper slag phase takes place sequentially (Fig. 4), according to:

\[
\text{(Si)}_{\text{Fe}} + \text{O}_2 \rightarrow (\text{SiO}_2)_{\text{slag}} \quad (\text{Eq} \ 12)
\]

\[
2\text{(C)}_{\text{Fe}} + \text{O}_2 \rightarrow 2\text{CO} \quad (\text{Eq} \ 13)
\]

\[
\text{(Mn)}_{\text{Fe}} + \frac{1}{2}\text{O}_2 \rightarrow (\text{MnO})_{\text{slag}} \quad (\text{Eq} \ 14)
\]

\[
2\text{(P)}_{\text{Fe}} + \frac{1}{2}\text{O}_2 \rightarrow (\text{P}_2\text{O}_5)_{\text{slag}} \quad (\text{Eq} \ 15)
\]

It should be emphasized that the exact transfer mechanisms are obscure and tend to remain so, due both to the opacity of the system and to the experimental difficulties and restrictions involved in direct measurements of important process variables at 1600 °C (2910 °F). However, the fact that the carbon drops linearly with time during the blow (following silicon elimination) indicates that the rate of oxygen supply controls the rate of decarburization; this is evident except at very low carbon levels, where the curve in Fig. 4 tails off with time.

Thus, towards the end of a BOF blow, the transport of dissolved carbon up to the fire point, where the oxygen jets impinge on the metal bath, has difficulty keeping up with the supply of oxygen. As a result, oxygen begins to dissolve in the steel bath at an increasing rate as the carbon-oxygen reaction heads away from the equilibrium curve for (C)_{eq} and (O)_{eq} in contact with a carbon monoxide environment at a partial pressure of 0.1 MPa (1 atm). Figure 5 illustrates the trajectory of the carbon-oxygen evolution as a function of process. The BOF-related curves start moving sharply higher as carbon levels drop below about 0.07 wt% C. The rapid increases in dissolved oxygen imply dirtier steels because greater amounts of deoxidizers (Al, Fe-Si) are needed to remove this oxygen, which is in the form of condensed oxide inclusions.
Second-Stage Refining and Technology Advances. The recognition that the stirring being provided by the top-blown jet of a BOF furnace toward the end of the refining process was inadequate, together with the development of the Savarde-Lee shrouded tuyere (Ref 4), triggered a remarkable change in the technology of these oxygen-blown vessels. The tuyere development work made possible and practical the bottom blowing of low-pressure oxygen at high flow rates through a series (typically eight) of tuyeres set in the bottom of the furnace. Each tuyere consists of a central pipe for the oxygen jet and an annular space for injecting a hydrocarbon (such as methane) to form a solid mushroom of steel (Fig. 6). This mushroom protects the refractory base from the fluxing effects of FeO and has allowed the revived use of the Bessemer vessel of 1856 (Ref 5), except that pure oxygen rather than air is injected.

The first North American licensee named this process the quick-quiet basic oxygen process, or Q-BOP. The bottom-blown oxygen jets provide better mixing, lower turn-down carbons (of the order of 0.01 wt% C), higher yields (less FeO in slag), and shorter processing times (for example, 14 versus 17 min/ton). One drawback, however, is higher levels of turn-down hydrogen in the steel. This is caused by the endothermic cracking of the methane that is needed for the formation of the protective thermal accretions, or mushrooms (Ref 6). Higher levels of dissolved hydrogen can be deleterious for heavy-section products such as pipeline steels and ship plate products; postrefining stir with argon is sometimes favored for steels with these applications.

Another feature of these bottom-blown vessels is the need to inject a fine powdered lime simultaneously with oxygen. Top charging of lime particles or lumps in a similar manner to BOF operations leads to unacceptable foaming and slopping.

A wide variety of other processes have been spawned that take advantage of some features of both top- and bottom-blown vessels. In the Kawasaki basic oxygen process (K-BOP) operation, 30% of the oxygen is soft blown from a multihole lance set high above the steel bath, with the remainder injected through the base of the vessel using shrouded tuyere technology. This allows low turn-down carbons (of the order of 0.02 to 0.04% C), together with higher scrap-melting capabilities (for example, 33% versus 30% of the charge). Other similar technologies, such as the German Kloeckner metallurgy scrap (KMS) process, are also in use.

The improved scrap-melting capability of such vessels is enabled by the burning of a higher proportion of effluent carbon monoxide to carbon dioxide within the upper reaches of the vessel itself. Part of the attendant heat can be usefully transferred back to the metal bath, allowing more scrap to be melted. Because scrap generally represents a less expensive source of iron units versus hot metal from the blast furnace, such operations can be profitable, even though they are more technically complex to operate.

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Practically all BOF (or oxygen-blown method (OBM) or Linze-Donovitz (LD) method) steelmaking operations in North America now use bottom-blown gas injections at least to stir the steel bath. For example, nitrogen, argon, or carbon dioxide can be blown through submerged injector ports, plugs, or nozzles of various proprietary designs. The Sumitomo top and bottom blowing (STB) process, in which CO2/N2 mixtures are bottom blown at about 5% of the flow of the top-blown oxygen in a BOF-like vessel, is a good example of this concept. The STB process increases yields and lowers turn-down carbons, thus approaching the performance of Q-BOP vessels.

Electric Furnace Steelmaking. Although integrated steel plants use oxygen-blown steelmaking vessels, many smaller steelmaking operations rely on return scrap steel (versus iron ore) as a primary source of material. For such operations, electric arc furnaces offer economic and technological advantages. These furnaces were originally considered appropriate for the production of tool and alloy steels, but they are also able to produce low-carbon steels of high quality. Currently, 30% of the steel production in North America derives from scrap recycling through melting and refining operations in electric arc furnaces. One difficulty is that residuals, such as copper and tin in return scrap, are not diluted with a virgin hot-metal source in electric furnace steelmaking. However, with the introduction of prereduced ores (Ref 7) of low gangue, or impurity levels (for example, >2% SiO2) such problems can be mitigated.

Recent technological advances have stressed the role of the furnace as a melter rather than a refiner. Water-cooled panels are required to carry the ultrahigh-power kVA levels of modern furnaces.

Ferroalloy/Deoxidizer Additions. No matter which process is used, the raw steel poured from a furnace into a teeming ladle is too highly oxidized for immediate use because it contains about 0.04 to 0.1 wt% O. This level would cause blowholes in the steel if it were then solidified. Steel deoxidants such as aluminum, ferrosilicon, or carbon are therefore required to bring dissolved oxygen contents down to acceptable levels through precipitation of condensed oxides as inclusions. At the same time, additions of other ferroalloys (for example, Fe-Mn, Fe-Nb, Si-Mn, Fe-V) are made as needed to meet the chemical specifications required for the variety of steel grades that are currently produced by any integrated steel company.

These bulk additions (13 to 100 mm, or ½ to 4 in., in diameter) either melt quickly (~40 to 120 s) or dissolve slowly (~60 to 360 s), depending on whether their melting ranges are below or above the steel bath temperature (typically 1570 to 1600 °C, or 2850 to 2910 °F) (Ref 8). Some are buoyant.
Fig. 5 Equilibrium curve for dissolved carbon and oxygen compared with operational carbon-oxygen trajectories for various steelmaking processes. The isopercemtage error lines illustrate the relative importance of carbon to oxygen diffusion on carbon-oxygen kinetics. Q-BOP, quick-basic oxygen process; LBE, lance bubbling equilibrium; KMS, Kloeckner Metallurgy Scrap; BOF, basic oxygen furnace. Source: Ref 1

Fig. 6 Thermal accretions (mushrooms) formed in Q-BOP steelmaking operations using the Savarde-Lee shrouded tuyere

(for example, aluminum and ferrosilicon) and tend to float, while others, such as ferroniobium and ferrotungsten, sink rapidly (Ref 1). In either case, thorough metal mixing throughout the teeming ladle is needed (Ref 1). These large bulk additions are commonly added via alloy addition chutes during the last half of a 4 to 8 min furnace-tapping operation. Carryover of slag from the BOF into the ladle can make the recoveries of aluminum and ferrosilicon to the steel highly variable because slag deoxidation as well as metal deoxidation can occur. For these reasons, alloy addition sequencing is important, as are slag control techniques, to limit the net carryover of slag.

Ladle Steelmaking. The increasing need to produce quality products that meet much tighter chemical and physical specifications has led to major changes in steelmaking practices during the last two decades. These changes have centered on modifications to liquid steel within the ladle; therefore, this area of technology is known as ladle steelmaking.

To illustrate the critical nature of correct chemistry, aluminum-killed steels for deep-drawing operations require dissolved aluminum levels that range between 0.03 and 0.04% (Al)_{eq}. The aluminum precipitates with dissolved nitrogen as aluminum nitride during subsequent batch-annealing operations. This precipitation controls grain growth and leads to steel with a fine grain structure and good deep-drawing qualities. Higher or lower levels of dissolved aluminum lead to poor performance indices (Fig. 7).

Even tighter specifications were required for high-strength low-alloy steels, which were introduced to compensate for weight reductions (that is, thinner gages) on automobile parts during the energy crises of the 1970s. Specifications called for dissolved niobium levels of 0.03%, a difficult target without close control of steel deoxidation procedures.

The production of interstitial-free steels for deep drawing (which are described in the article "High-Strength Structural and High-Strength Low-Alloy Steels" in this Volume) require carbon and nitrogen levels less than 50 ppm and controlled additions of titanium and/or niobium to scavenge carbon and nitrogen. To meet such stringent demands, secondary steelmaking processes, focusing on the teeming ladle, have been developed. Of these, the ladle furnace is used for melt reheating and temperature control. The Ruhrstahl Hereaus (RH) degasser, or tank degasser, is used to reduce
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Fig. 8 Effect of lime powder injections on the quality of steel. RH, Ruhstahl Hereaus process

![Graph showing the effect of lime powder injections on the quality of steel.](image)

Dissolved (C,O,H,N)_x levels. A third type of ladle station provides strong stir facilities by using argon and porous plugs set in the base of each teeming ladle, slag rake-off equipment, and wire feeding that allows precise additions of alloying elements, such as aluminum.

Third-stage refining, although still novel, has been conducted by, among others, Sumitomo Metals Industries; it is also known as the injection refining (IR) process (Ref 1). First lime and then calcium silicide are fed pneumatically through a vertical lance into the teeming ladle. A refractory-lined hood placed over the surface of the steel prevents ingress of atmospheric oxygen. As the relatively large lime particles rise through the melt, they cleanse it by collecting the essentially stationary smaller-diameter (~1 to 10 μm, or 40 to 400 μm) products of deoxidation. The results of ternary refining are shown in Fig. 8. The number of clusters is greatly reduced after RH degassing followed by strong bubbling. The clusters are totally eliminated with strong bubbling and lime additions.

A final injection of calcium silicide can be used to convert any remaining solid aluminum products of deoxidation into liquid calcium aluminate (preferably 12CaO-7Al₂O₃) inclusions (Ref 9). Such inclusions pass easily through metering nozzles into the tundish and from there into the mold of a continuous casting machine.

By the end of these ladle refining operations, the total residuals within the steel can be brought down to very low levels (~50 ppm total residuals for (S,O,N,H,P)ₚ₆) (Ref 10). The difficulty in the final liquid metal processing steps is to maintain this level of physical and chemical quality prior to final solidification in the continuous casting machines.

Tundish Metallurgy and Continuous Casting. The flow of steel from the tundish into the caster is shown in Fig. 9. Figure 10 illustrates the potential sources of contamination of purified steel emptied from the teeming ladle into the tundish. Using a sliding gate nozzle, metal is metered from the bottom of the teeming ladle into a tundish. This nozzle has to be shrouded with argon to avoid air infiltration, steel reoxidation, and the consequent generation of inclusions.

The tundish, in addition to acting as a metal distributor to two or more casters, serves as a further cleansing unit for inclusion removal. Therefore, current practices often use dam and weir combinations to modify the flow of steel within the tundish to enhance inclusion separation. This has led to a trend toward tandishes with larger volumes and thus longer residence times for a given throughput (for example, 60 tonne, or 66 ton, tandishes with a 7-min residence time for a 320 tonne, or 350 ton, ladle full of steel). A typical velocity field for a single-port water model tandish using the computational fluid dynamic code METFLO (Ref 11), is illustrated in Fig. 11. The associated inclusion separation ratios (defined as the number of inclusions leaving per the number of inclusions entering a tandish) as a function of inclusion rise velocity are also given in Fig. 12. Flow modifiers have no influence on the very small inclusions collected by ternary refining (or by filters), but they can help clean the steel of midsize inclusions in the 50 to 200 μm (2 to 8 mil) range (Fig. 12). For larger inclusions with Stokes rising velocities greater than 5 mm/s (0.2 in./s), these flow controls are not needed for the set of operating conditions noted.

Tundishes are normally fitted with insulating covers to conserve heat. For highly deoxidized steels, they are protected with an argon gas cover to reduce reoxidation and inclusion formation. An artificial slag can also be added to absorb those inclusions that are floating out.

Contrary to popular belief, many inclusion clusters can reach large sizes within the tundish. Because they can be made up totally of alumina, large clusters are most likely the agglomerated products of deoxidation. Figure 13 presents data analyzing the large inclusions present in an aluminum-killed steel in a 60 tonne (66 ton) slab casting tundish not fitted with flow modifiers. A typical histogram of the inclusions, based on an online electric sensing technique using a Liquid Metal Cleanliness Analyzer (LMCA) (Ref 12), is compared with data from Japan for a wire quality steel (Ref 13). The slime extraction analysis technique (dissolution of large sample of steel by ferrous chloride, with elutriation to collect unreacted inclusions of alumina and/or silicates) was used for the Japanese data.

Microscopic techniques are inappropriate for the size range shown in Fig. 13, and slime extraction techniques require three days to complete. Nevertheless, such analysis is important because large inclusions can have a deleterious effect on the surface quality, paintability, and zinc-coating characteristics of steel sheet. Similarly, as such inclusions (of alumina or manganese silicates, and so on) are rolled out into long stringers, the transverse properties of steel sheet or plate, such as percent elongation and ultimate tensile strength, are severely compromised, as is metal formability. Consequently, the modification of these inclusions into calcium aluminate inclusions, which are refractory at rolling temperatures.
and retain their original spherical shape following rolling, is much preferred (Ref 9).

For other critical applications, the presence of inclusions with a diameter greater than about 50 \( \mu \text{m} \) (2 mils) needs to be prevented. Figure 14 shows a break in a steel wire fabricated for a steel-belted automobile tire (Ref 13). There is a move in the industry to filter steel for such applications to help eliminate inclusions under about 50 \( \mu \text{m} \) (2 mils) in size, which are not susceptible to flow modifiers.

**Mold Metallurgy.** The last opportunity for inclusions to be removed is in the mold. Metal enters the mold of a continuous caster through a submerged entry nozzle (Fig. 9); the ports of the nozzle are often angled upward in order to direct the exiting jets of metal up toward the steel surface. There, a layer of lubricating slag from fused mold powder further assimilates inclusions while it simultaneously protects the steel from reoxidation and provides lubrication between the forming shell of the steel and the surfaces of the oscillating mold.

It is preferred that the final structure of the solid steel be equiaxed rather than columnar so that cracking of the billet, slab, or bloom during unbinding operations is less likely. Precise control of the metal superheat temperature is needed to prevent dendrite tips that are broken from the advancing columnar freezing front of steel from remelting. The dendrite tips are needed to act as nuclei for grain growth within the remaining melt. Electromagnetic stirring is also used to enhance uniformity of chemistry and structure, and to eliminate centerline segregation of solute-rich material. The cast steel is then cut with travelling oxytorches into slabs, billets, or blooms of appropriate length for further processing. The slabs are about 4 m (13 ft) long, 1 m (3.3 ft) wide, and 100 mm (4 in.) thick. These slabs are inspected and then charged to a slab reheating furnace for subsequent hotrolling operations. Alternatively, in plants with advanced steelmaking practices where slab surface quality is guaranteed to be acceptable (that is, no scarfing is required), the slabs can be directly charged into the slab reheate furnace.

**Future Technology for Liquid Steel Processing Operations.**

Because of the high capital cost of the blast furnace, melt shop, and hot-rolling mill complex, major research and development efforts are being made within the industry, with the objective of eliminating the number of process steps needed to produce a final product. Figure 15 shows past, present, and possible future process steps for the production of flat-rolled sheet. The object is to reduce the number of major processes down to two: direct steelmaking and direct, or near-net shape, casting. In direct steelmaking, the aim is to feed coal (rather than coke), together with iron ore pellets and lime flux, into an autogeneous reactor to produce iron that contains perhaps 2% C. In direct casting, the aim is to develop the technology needed to directly cast steel sheet perhaps 5 to 10 mm (0.2 to 0.4 in.) in thickness, at tonnage rates of 100 to 200 tonnes/h/ft width (35 to 70 tons/ft/width). Such performance characteristics would match those of the big slab casters of the present, but would have a dramatic impact on the capital and operating costs of the integrated steel plant of the future.

**Processing of Solid Steel.**

As with liquid steel, several processing operations are required to convert steel into its wide variety of finished forms. Figure 15 shows the sequence of operations for flat rolling. After continuous casting and inspection, followed by slab reheating in the reheating furnace, 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 gauges, hot-rolled strip is cold-rolled, which is followed by annealing and by various coating processes to protect against corrosion; coatings include zinc, tin, zincalumne, paint, enamels, and so on. Slabs cut from the continuous casting machine are reheated to bring the steel to about 1200 °C (2190 °F).
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Fig. 10 Potential sources of contamination in the continuous casting process

Hot Rolling

Hot rolling is carried out with the steel in its γ, or austenite phase. Steel is evidently plastic and particularly malleable at the temperatures employed, which 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 thick slab to 2 mm thick hot strip) with relatively small force. Following hot rolling, the steel transforms into its low-temperature α, or ferrite, phase (plus other constituents). 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.

In early integrated steel mills, hot rolling traditionally began with the breakdown of cast ingots into rectangular slabs about 200 mm (8 in.) thick or square billets about 200 x 200 mm (8 x 8 in.) in cross section. With the gradual replacement of ingot casting by continuous casting (except for tool steels and other specialty or low-tonnage grades), the slabbing, or breakdown, stage of hot rolling has gradually disappeared from most mills. Layout of a modern hot strip mill is shown in Fig. 16. Hot rolling begins with roughing, which occurs at temperatures from 1200 °C (2190 °F) down to about 1100 °C (2010 °F). During roughing, slabs about 6 to 8 m (20 to 26 ft) long and 250 mm (10 in.) thick are converted into transfer bars about 30 to 50 mm (1.2 to 2 in.) thick and up to 40 or 50 m (130 or 165 ft) long. Round or square billets are transformed by analogous steps into bars about 100 m (330 ft) in length.

Finish rolling, or finishing, is then carried out in a five-, six-, or seven-stand hot mill (Fig. 16), with finishing stand temperatures as low as 900 or 800 °C (1650 or 1470 °F). By this means, the transfer bars are converted into strips about 2 to 3 mm (0.08 to 0.12 in.) in thickness and 600 m (2000 ft) long, at a productivity level of about 100 tons/h per meter of steel strip width (Ref 14). The hot strip is coiled, while plate grades are retained in their rectangular form at thicknesses of about 10 to 30 mm (0.4 to 1.2 in.). In a similar manner, long products are either coiled if they are round and of small cross section (about 6 mm, or 0.24 in., in diameter), or cut to length if they are thicker or of irregular cross section, such as angle and channel shapes.

Critical Temperatures. The three varieties of controlled rolling that have been developed to date rely on the recognition of the three critical temperatures of steel rolling. The first of the three temperatures is the austenite recalescence point, or Tnr. At temperatures above Tnr, the austenite recalesces into ferrite phase as a result, the grain size is refined, and the work hardening accumulated within the roll pass is eliminated. This temperature can be detected by examining microstructure and hardness testing at different temperatures (Fig. 17). Below the Tnr, the recrystallization temperature of austenite no longer takes place during rolling passes. Work hardening, or strain, accumulates as a result, and the flow resistance or rolling load begins to increase more sharply with decreasing temperature (Fig. 17 and 18).

The second critical temperature, the upper critical temperature, or Ar, defines the start of an isothermal transformation on cooling (the r comes from the French refroidissement). The third temperature, the lower critical temperature, defines the end of the austenite-to-ferrite phase transformation and is known as Ar. It should be noted that these two critical temperatures do not correspond to the Ar and Ar, values determined on annealed samples using classical dilatometry, for example, because the deformation introduced by rolling modifies the transformation behavior of the steel. Instead, Ar and Ar, can be determined with the aid of deformation dilatometry, which applies a compressive strain to the sample prior to...
the initiation of cooling, or by the torsion simulation of rolling (Fig. 17 and 18).

Precipitation of Carbonitrides and Sulphides. Many of the particles that are precipitated during cooling after continuous casting are redissolved during reheating in the slab reheat furnace. These include AlN, MnS, Nb(C,N), Ti(C,N), Ti₃C₂, TiS, and VN. During subsequent hot rolling, these precipitates are produced readily because the dislocations introduced during rolling act as nucleation sites for strain-induced precipitation. These particles are only about 2.5 nm (0.1 μm) in diameter when they appear, but they can grow or coarsen up to diameters of 10 to 20 nm (0.4 to 0.8 μm). The particles take several seconds to form; therefore, they are not produced during rolling operations of short duration. In general, these particles only play a role at temperatures below 1000 °C (1830 °F); that is, during finishing. The strain-induced precipitation of MnS is important in the processing of electrical steels, while that of Nb(C,N), Ti₃C₂, and TiS is important in the rolling of interstitial-free steels, and that of Nb(C,N) (and to a lesser extent TiC and VN) is important in the controlled rolling of microalloyed or high-strength low-alloy steels (Ref 15, 18).

Precipitation is necessary because recrystallization can only be arrested during finish rolling, and only if a copious number of precipitates form during passage of the strip between successive mill stands. A high density of precipitates is promoted by the occurrence of cooling between passes (which increases the driving force for precipitation) and interpass intervals of about 10 s or more. As a result, a Tₚₑ is only displayed by steels containing niobium, titanium, or vanadium and, furthermore, only when sufficient time is provided during finish rolling for the precipitates to nucleate and grow (Ref 18). This means that recrystallization is most readily arrested during rolling in slow reversing mills, such as plate and Steckel mills, while precipitation plays a much smaller role in tandem mills, such as hot strip, rod, and other mill installations where interpass times are short (∼0.5 s or less).
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Conventional controlled rolling (CCR) was the first type of controlled rolling to come into regular commercial use. About 8 to 10% of the total steel tonnage rolled annually is now produced in this way. This process was originally developed for the production of plate grades for the manufacture of oil and gas pipelines, for which the required minimum yield strengths were 350 MPa (50 ksi), 420 MPa (60 ksi), and 490 MPa (70 ksi) (Ref 15). Because of the need for good weldability, low concentrations of carbon and carbon equivalents were specified. These were readily obtained by reducing carbon concentrations to 0.06% or 0.07%, small amounts of niobium (about 0.04%), in combination with vanadium (up to 0.1%) and molybdenum (up to 0.30%), were added for higher-strength grades.

During roughing operations, the coarse reheated austenite grains in a slab are first refined by repeated recrystallization, bringing the grain sizes down to about 20 μm (0.8 mil) or less. The transfer bar can then cool below the T_r, during transfer from roughing to the finishing facilities. When rolling is restarted or continued below the T_r, recrystallization is no longer possible, and the austenite structure is progressively flattened in an operation known as pancaking. For pancaking to be successful, the accumulated reductions applied in this temperature range must add up to at least 80%.

Finally, when the flattened austenite grains go through their transformation to ferrite, the ferrite produced has a very fine grain structure because of the large number of nucleation sites available on the expanded surfaces of the pancaked austenite grains. This leads to ferrite grain sizes in the range of 5 to 8 μm (0.2 to 0.3 mil). The fine-grain ferrite is responsible for the attractive combination of good toughness properties and high yield strengths (Ref 15, 18). It should be stressed that austenite pancaking is only possible in the absence of recrystallization, and its arrest is caused by the copious precipitation of Nb(C,N) during delays between mill passes.

Recrystallization Controlled Rolling (RCR). As described above, controlled rolling is generally based on the use of low finishing temperatures (that is, in the vicinity of 800 to 900 °C, or 1470 to 1650 °F), with the result that fine ferrite grain sizes appear after transformation. However, such finishing is inappropriate for certain products, such as heavy plates and thick-walled seamless tubes (Fig. 19), that cannot be finished at such low temperatures in the hot-rolling range due to excessive rolling loads. For such applications, it is possible to produce the fine microstructures required by carefully controlling the recrystallization of austenite and arranging for it to occur at successively lower temperatures during finish rolling (Ref 19). These temperatures are nevertheless above 900 °C (1650 °F) and thus are higher than those employed in CCR.

Two requirements must be met for the RCR process to be successful. One is that the recrystallization not be sluggish, so that the times required are not too long. This is achieved by employing vanadium rather than niobium as an alloying element. Vanadium acts as a grain refiner without bringing recrystallization to a complete stop, as niobium is inclined to do. The second requirement is that grain growth be prevented after each cycle of recrystallization; this grain growth can negate the refining effect of recrystallization at lower and lower temperatures. For this purpose, sufficient titanium is added to have about 0.01% available for the formation of fine particles of TiN during cooling after continuous casting (Ref 20). When this dispersion has an appropriate size and frequency distribution, it can completely prevent grain growth of the austenite after each cycle of recrystallization. The fine austenite grains, in turn, transform into relatively fine-grain ferrite, for example, 8 to 10 μm (0.3 to 0.4 mil) in diameter, leading to mechanical properties in the hot-rolled product that are acceptable for many purposes.

Dynamic Recrystallization Controlled Rolling (DRCR). When the interpass time is short, as in the case of rod, hot strip, and certain other rolling processes (Fig. 20), insufficient time is available for conventional recrystallization during the interpass delay. The amount of carbide precipitation that can take place is also severely limited. As a result, an alternative form of recrystallization is initiated. This is known as dynamic recrystallization, and it involves the nucleation and growth of new grains during (as opposed to after) deformation (Ref 21, 22). This also requires the accumulation of appreciable reductions, of the order of 100%, to enable the recrystallization process to spread completely through the microstructure inherited from the roughing process. Austenite grain sizes as small as 10 μm (0.4 mil) can be achieved with DRCR (Ref 23).

Low-temperature finishing by DRCR has the advantage of producing finer ferrite grain sizes after transformation than CCR; that is, 3 to 6 μm (0.12 to 0.24 mil), as
Fig. 15 Past, present, and future steel processing steps

opposed to 5 to 8 μm (0.2 to 0.3 mil) for the latter process (Ref 21). However, such low-temperature finishing increases the rolling load, and it can also make mill control more difficult because of the load drop associated with the initiation of dynamic recrystallization. It is important to note that under industrial rolling conditions, CCR, RCR, and DCR can all occur to different degrees during a given operation. This can happen when the processing parameters have not been optimized so as to favor only strain-induced precipitation and austenite pancaking in the case of CCR, conventional recrystallization in the case of RCR, and dynamic recrystallization in the case of DCR.

The Stelco Coil Box. One of the problems associated with batch processes such as the rolling of both long and flat products is the temperature rundown that develops (between the head and tail of a transfer bar, for example). Such a gradual decrease in temperature can lead to gage and flatness problems, as well as to gradients in microstructure characteristics (and therefore in the mechanical properties) along the workpiece. One solution to this problem has involved the introduction of a coil box between the roughing and finishing stands of a hot strip mill (Fig. 21). When the transfer bar, which is 30 to 50 mm (1.2 to 2 in.) thick, arrives at the coil box, the leading edge is deflected and curled into a circular shape, and the entire bar is wound into a coil without a mandrel or spool being required. The coiled shape of the workpiece enables it to cool much more slowly as the bar is slowly fed (tail end first) into the hot strip mill. This technology has led to a significant improvement in the uniformity of the dimensions and properties of the final product, as well as to a decrease in the energy required for hot rolling.

Cooling Beds, Runout Table Cooling, and Coiling. Following hot rolling, the workpiece 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. Figures 22(a) and (b) show a laminar flow cooling system used on a hot mill. For rods it is carried out in water boxes and along cooling lines employing large volumes of forced air (Fig. 23). Except for certain grades of stainless and electrical steels, such 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 at present in the use of accelerated cooling to promote the formation of appropriate microstructures. For most steel products, in fact, this process is the least expensive way to increase the strength.

When the transformation product consists largely of ferrite, rapid cooling decreases the ferrite grain size obtained from a fixed hot-rolling schedule. This is because of the hysteresis involved in phase transformations, as a result of which the actual (as opposed to equilibrium) transformation temperature displayed on cooling decreases as the cooling rate is increased. Lower transformation temperatures, in turn, lead to finer ferrite grain sizes, in part because the growth rates are lower at lower temperatures, but also because the ferrite nucleus density increases with increasing supercooling below the equilibrium transformation temperature.
When the transformation product consists largely of pearlite or contains appreciable volume fractions of pearlite, more rapid cooling leads to the formation of finer pearlite, which is associated with higher strength. However, if the cooling rate is too rapid for a given chemistry, some bainite or even martensite can form. Unless these transformations are carefully controlled, such structures lead to a lack of toughness and ductility and are therefore generally avoided. Nevertheless, B-modified bainitic steels are employed for the production of high-strength heavy plate (700 to 900 MPa, or 100 to 130 ksi, yield strength in the as-rolled condition); the carbon level in these steels is reduced to about 0.02% to improve toughness. Similarly, fully martensitic steels can be produced by quenching (a separate and therefore fairly expensive operation), in which case the brittleness is reduced by an appropriate tempering treatment.

Precipitation During Cooling and Coiling. The solubility of all the precipitate-forming elements in steel decreases as cooling progresses (Ref 18). Thus, carbonitrides and sulfides such as AlN, Fe,C, MnS, Nb(C,N), Ti(C,N), Ti5C2S2, TiS, and V(C,N) all tend to form, either on the run-out table or cooling bed, or after coiling. Because precipitate nucleation and growth take time (for example, 1 to 10 s for nucleation, and 10 to 100 or 1000 s or more for growth, depending on the temperature), the amount and type of precipitation that takes place after hot rolling are sensitive functions of the cooling rate and conditions of holding. Thus, rapid cooling on the runout table suppresses precipitation, although some particles are inevitably formed during the austenite-to-ferrite transformation, because the solubilities in ferrite are appreciably lower than the respective levels that pertain to the austenite. The cooling temperature is also of considerable importance. Relatively high cooling temperatures, of the order of 750 °C (1380 °F), followed by the slow cooling rates associated with the geometry of coils, favor the precipitation of the carbonitrides (for example, AlN). Low

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**Fig. 16** Layout of a 2130 mm (84 in.) continuous hot strip mill. Source: Ref 14

**Fig. 17** Stress-strain curves of torsional simulation for an average schedule of a Steckel hot mill. The pass number is shown above each flow curve. Source: Ref 17

**Fig. 18** Mean flow stress as a function of 1000/°F, where °F is the absolute pass temperature. Region I corresponds to the temperature range where recrystallization occurs after each pass; region II falls between the non-recrystallization temperature and Ar3, the upper critical temperature; region III is the inter-critical temperature range; region IV lies below the Ar3 of lower critical temperature. Source: Ref 17
coiling temperatures, of the order of 550 °C (1020 °F), on the other hand, prevent AlN formation and keep these elements in solution for precipitation during annealing after cold rolling. The coiling temperature also determines the mean size and number of the particles that form; the former decreases and the latter increases as the temperature is lowered. These considerations are important because the final grain size after recrystallization and grain growth is directly proportional to the mean particle size for a given chemistry (that is, containing a given volume fraction of precipitate).

**Warm Rolling**

In recent years a renewed interest has developed in warm rolling, that is, the finish hot rolling of steel in the high-ferrite, as opposed to the low-austenite, temperature range. Warm rolling is possible because ferrite is actually softer than austenite at a given hot-rolling temperature. From the example shown in Fig. 24 it is evident that the ferrite in an interstitial-free (IF) steel has as little as half the flow resistance of the austenite prior to transformation. Such a large difference in flow stress can lead to serious gage and control problems when rolling is carried out in the vicinity of the γ-to-α transformation. These problems are avoided, however, if rolling is suspended during cooling through the intercritical range and resumed only when the steel has cooled below Ar1.

The example given above is extreme because the low carbon level of an IF steel (about 30 ppm) means that the intercritical temperature range is reduced to as little as 30 °C (85 °F), and therefore the flow stress drop associated with passage through this range is very sharp. In conventional steels, the difference between the Ar1 and Ar3 temperatures is in the range of 100 °C (180 °F) or more. In such cases, the fully ferritic material is significantly colder than its fully austenitic counterpart, and thus the ferrite has a resistance to flow that is only moderately less than that of the austenite.

**Fig. 20** Finishing stands of a 2130 mm (84 in.) hot strip mill. Courtesy of Mesta Machine Company

**Fig. 21** Coil box of hot strip mill. (a) Position on delay table. (b) Schematic of coil box function. Source: Ref 14, 24

The warm rolling of IF steels is of commercial interest because lower reheating and rolling temperatures can be used, leading to lower scale losses and energy consumption rates in the slab reheat furnace. Furthermore, the textures developed during the warm rolling of ferrite do not differ appreciably from those produced during the cold rolling of the same phase, and this rolling step can therefore be employed for the production of steels with excellent formability characteristics.
Cold Rolling

About half of all rolled steel products are sold in the as-hot-rolled condition. This includes such obvious items 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. In the cold rolling of flat products, numerous advances have been made in equipment and processes that have allowed for improved flatness and consistency of gage along the length of a coil. These advances include hydraulically inflatable rolls for control of the amount of crown, six-high mills with tapered backup rolls that can be inserted and withdrawn laterally as required, as well as a variety of roll-bending techniques (Fig. 25).

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 to be carried out, such as in the manufacture of cans or the deep drawing of auto body parts, cold rolling must be followed by annealing. 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, also known as AKDQ, or IF steels), annealing also brings about an increase in the normal anisotropy (R value), which leads to significant further increases in the deep drawability.

Annealing

Batch Annealing. The annealing of coils weighing 9 to 27 tonnes (10 to 30 tons) is necessarily a very time-consuming operation. Typical heating and cooling times are of the order of 2 and 3 days, respectively, so that the rate of temperature change is about 12 °C/h (22 °F/h) during heating and −8 °C/h (−14 °F/h) during cooling. Consequently, a total process time of nearly 5 days is involved. Because of the considerable capital, maintenance, and energy costs associated with such heating operations (Fig. 23), the optimization of heating and cooling schedules to improve the productive capacity of these units is a subject of great interest at present.

The principal mechanism associated with batch annealing is recrystallization, which eliminates the strain hardening introduced in the previous rolling operations. Once initiated, at temperatures of 600 to 650 °C (1110 to 1200 °F), it takes only minutes to spread through the material and replace the grain structure flattened by rolling with equiaxed, strain-free grains. Although precipitation coarsening and particle solution and reprecipitation also occur, they are not of particular importance for most grades. For AKDQ steels, on the other hand, the characteristics of precipitation and of particle coarsening must be carefully controlled so that the grain orientations associated with high formability (that is, the {111}{110} and to a lesser extent the {111}{112} texture components) are favored during recrystallization and can in this way replace the other sets of grain orientations inherited from the rolling operation. This is brought about by pinning the undesirable [100]-oriented grains during heating through their optimum growth temperature range by means of AlN particles. These form during heating from the supersaturated Al and N held in solution as a result of the relatively low cooling temperatures (550 °C or 1020 °F) employed for the AKDQ grades. The AlN particles gradually redissolve and coarsen as the temperature is further increased during annealing, permitting growth of the {111}-oriented grains within the temperature range that favors this orientation.

Continuous Annealing. With the trend toward more and more continuous processing, batch annealing is gradually being replaced by continuous annealing (Fig. 26). The prime advantage of this process is the considerable increase in product uniformity along the length of a given coil. This is of increasing importance as tolerances and allowable property variations are reduced as a result of the increasing automatization of forming processes. Because of the much shorter process times involved (for example, 2 min instead of 5 days), the heating and cooling rates are much higher (15 °C/s, or 27 °F/s). Negligible hold times are required at the maximum temperatures of 700 to 800 °C (1290 to 1470 °F), which are significantly higher than in the batch annealing process.

For commodity grades, the temperatures and heating and cooling rates are not of critical importance. By contrast, for drawing quality grades such as the niobium- and titanium-base IF steels, the process parameters must again be carefully adjusted for compatibility with the particular chemistries employed. For these steels, the favored texture components are {554}{225} and
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Fig. 25 Taper-adjusting method for crown control. Source Ref 24

(111)(112) and, to a lesser extent, (111)(110). These components differ slightly from those associated with the AKDQ steels and lead to still higher $R$ values. As for the AKDQ grades, the appearance and disappearance of precipitates (in this case, Nb(C,N) and Ti,Nb,C,S,) the mean sizes and volume fractions of these precipitates, and the amounts of niobium, titanium, carbon, and nitrogen remaining in solution must be carefully controlled if optimum product properties are to be produced. By tying up the carbon and nitrogen present in the form of carbonitrides and eliminating the yield drop in this way, low yield stresses are obtained, which lead to high initial work-hardening rates and $n$ values. These, in association with the high $R$ values that follow from the presence of the texture components described above, are responsible for the excellent drawability properties of these grades.

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Fig. 24 Factors influencing the warm rolling of steel. (a) Stress-strain curves for interstitial-free steel rolled according to an idealized schedule A (e = 2/$i$). (b) Dependence of stand S separating force on rolling temperature. Source: Ref 25
Fig. 26 Examples of continuous annealing configurations. (a) Continuous annealing line. (b) Entry looping section. (c) Heating, holding, and cooling zones. Source: Ref 24

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