## Chapter 1

# Introduction

In modern steelmaking and casting plants, steel is produced either in a basic oxygen furnace (BOF) or in an electric arc furnace (EAF). In a BOF, hot metal and scrap are blown by oxygen gas with a flux addition, such as lime, to remove carbon, phosphorus, sulfur, and silicon. A modern EAF produces steel by remelting and refining steel scrap and other raw materials, and also uses oxygen gas injection and lime addition. Fig. 1.1 [1] schematically shows a modern steelmaking and continuous casting facility. The steel melt with dissolved oxygen thus produced is tapped into a ladle, where it is deoxidized with ferroalloys, Fe-Si, Fe-Si-Mn, and/or metallic aluminum. The deoxidation products, such as silica, manganosilicates, alumina, aluminosilicates, aluminates and/or their composites, are largely removed from the melt by flotation. Whenever necessary, the deoxidized melt is further processed in a ladle furnace (LF) to remove any remaining suspended oxide particles (called non-metallic inclusions, or simply inclusions), to lower the sulfur content, and to adjust the melt's chemistry and temperature. Degassing of steel melt is done in vacuum refining facilities (RH, VAD, or VOD) to decrease hydrogen for crack sensitive grades and/or carbon for ultra low carbon grades to meet customer specifications.

The melt is then transferred from the ladle via a tundish into the mold of a continuous casting machine as shown by Yoshida *et al.* in Fig. 1.2 [2], and is solidified as slabs, blooms, or billets. In the last three decades, continuous casting has become a mature technology for the solidification of steel. Today, continuous casting has almost completely replaced ingot casting except for large castings. Continuous casting offers many advantages including better premium cast-metal yield, chemical homogeneity, and better inclusion cleanliness. In continuous casting process, the tundish plays an important role in linking the ladle with the continuous casting machine. A vast amount of published literature exists on the technology of continuous casting with a tundish, but a comprehensive description of tundish technology from both a fundamental and practical point of view is still lacking.

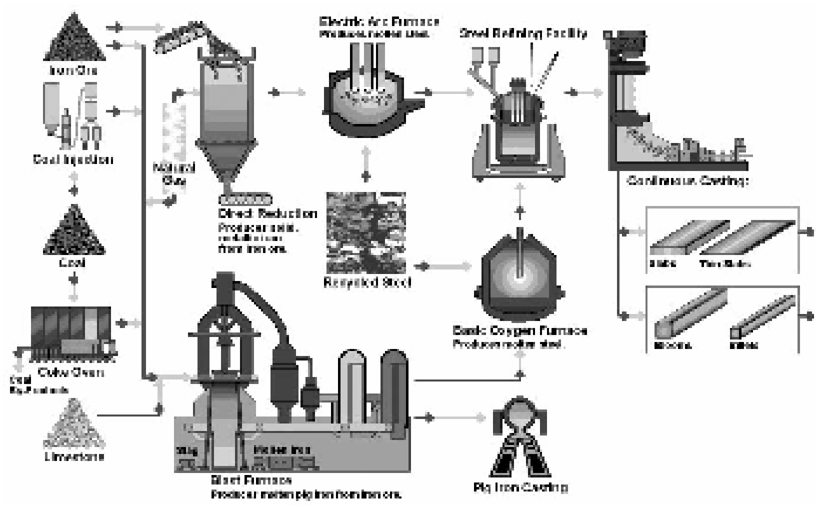


**Figure 1.1:** A typical steelmaking and continuous casting facility. [Ref. 1]

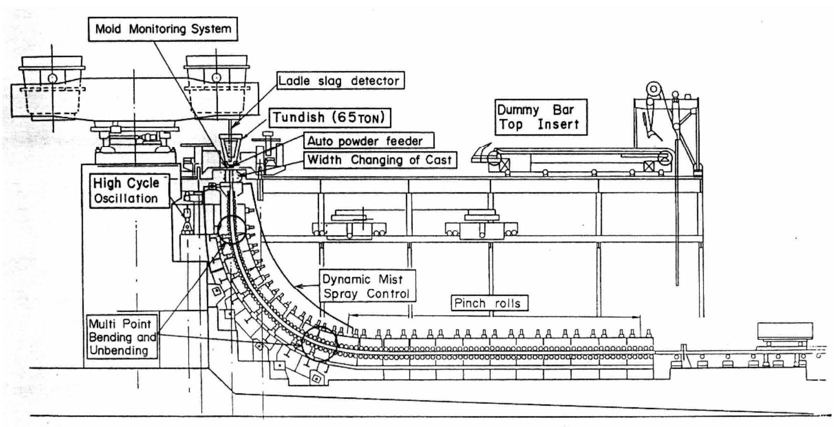


**Figure 1.2:** Continuous casting machine layout with tundish being installed between the ladle and mold. [Ref. 2]

The aim of this book is to give an overview of tundish technology as an important component of the steel production processes, with emphasis placed on the metallurgical aspects of producing clean steel. The first half of the book presents the fundamental and theoretical aspects of understanding tundish technology. The remainder of the book deals with operational aspects of the tundish. One chapter is also devoted to recent, emerging, and novel tundish technologies. Thus, the book is sufficiently fundamental to serve as a textbook for a graduate course on process metallurgy or as an important reference for a metallurgical researcher or plant engineer in a melting and casting plant. The book does not include any discussion of ladle refining and continuous casting, and coverage of tundish hardware details is rather limited.

Chapter 1 briefly reviews the importance of the tundish in transferring clean steel melt into a continuous casting mold; Chapter 2 deals with the thermodynamics and kinetics of the formation and removal of non-metallic inclusions in a tundish; Chapter 3 reviews the fluid flow and turbulence of steel melt in a tundish as influential factors in reducing inclusions; Chapter 4 deals with the fluid flow characterization of steel melt in a tundish; Chapter 5 describes physical and mathematical modeling of the melt flow in a tundish; Chapter 6 gives details of tundish operation; Chapter 7 discusses active melt temperature control in a tundish; and Chapter 8 touches on innovative new tundish technologies.

## 1.1 Ingot and Continuous Casting of Steel

Continuous casting has gradually replaced ingot casting over the years, reaching 50% of the annual crude steel production in Japan by 1978, in Italy and former West Germany by 1980, in Korea by 1982, in the UK by 1984, and in the USA by 1986. Large ingots for forgings and small lot production of diverse grades of steel are still produced by ingot casting. Great effort has been devoted to improving the surface and internal quality of continuously cast products to obtain a higher premium cast-metal yield. At the same time, continuous casting productivity was increased substantially to keep pace with the increasing raw steel production capacity. Currently, well over 95% of carbon steels and specialty steels are produced through continuous casting.

In ingot casting, a hollow cast iron mold with a square, rectangular, polygonal, or round cross section is set on the cast iron stool. Finished steel melt is poured from a ladle into the mold in two ways. One is from the mold top, called the top pouring into one mold at a time, and the other is from the mold bottom, called the bottom pouring or uphill teeming into single or multiple molds via the spout and runner bricks.

Typical installation of top and bottom pouring is shown by Eisenkolb and Gerling in Fig. 1.3 [3]. The melt stream in top pouring has more exposure to air and hence suffers from reoxidation. As the pouring stream impinges on the melt surface in the ingot mold, it carries reoxidation products and scum back into the bulk as macro inclusions. During mold filling, metal splash adheres to the mold walls and produces surface defects on the ingot skin, which later requires surface conditioning. In bottom pouring, the melt stream exposure to air, the entrainment of scum, and the occurrence of splash are reduced, but the melt stream contact with the refractory in the pouring spout and runner bricks is longer, which results in contamination of steel melt by inclusions of refractory origin. For large ingots for high end use where quality is important, inert gas shrouding or evacuation is employed during top pouring. For high end use small ingots, bottom pouring is common.

In ingot casting, fully Al-deoxidized steel melt is usually cast into a big-end-up mold with a hot top. Hot topping involves the combination of a thermally insulating board around the top periphery of the ingot and the addition of exothermic and thermally insulating powder on the molten metal. Hot topping retards the solidification of the ingot top, and supplies steel melt from the top to the core part of the ingot to fill the shrinkage cavity caused by steel solidification. During ingot solidification, characteristic crystals and segregation occur in different parts of the ingot as shown by Takenouchi in Fig. 1.4 [4].

Equiaxed crystals, being heavier than liquid metal, settle to the bottom of the ingot. They often trap the rising macro inclusions and carry them along. As solidification of the melt proceeds from the wall to the center of the mold, the formation of fine chilled crystals on the peripheral surface of the ingot is followed by the growth of columnar dendrites, which develop into branched columnar dendrites.

Driven by the difference in specific density, solute enriched melt begins to ascend in front of the branched dendrites, leaving inverse V-segregates along the contour of the solidification front. The core part of the ingot is filled with the sediment-equiaxed crystals from the top. As solidification proceeds, volume contraction in the core part causes the intermittent fall of the equiaxed crystals, and the solute enriched melt part fills the created void. The process results in the formation of

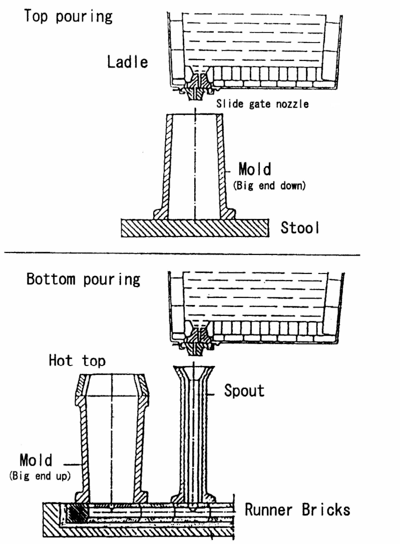


**Figure 1.3:** Top pouring and bottom pouring for conventional ingot casting. [Ref. 3] [Big-end-up molds for fully deoxidized steels]

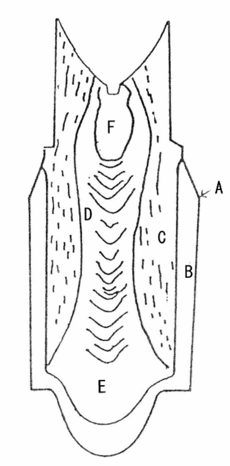


**Figure 1.4:** Crystal structure and segregation in top poured 75-ton killed steel ingot (A: chilled crystal skin; B: columnar dendrite crystal zone; C: branched columnar dendrite crystal zone with inverse V(or A)-segregates; D: equiaxed dendrite crystal zone with V-segregates; E: sediment equiaxed crystal zone with negative solute segregation and macro inclusions; and F: heavily solute segregated zone). [Ref. 4]

V-segregates, which are often accompanied by porosity or loose structure if the melt supply from the hot top is insufficient or is blocked by the bridging of solidified steel above the core. The degree of solute enrichment and loose structure in the equiaxed dendrites area depends on the superheat of the melt, the ease of melt feeding from the hot top, the height-to-thickness ratio, and the taper of the ingot.

The occurrence of macro inclusions can be reduced by pouring clean steel melt into the mold in a vacuum or under an inert atmosphere. Inverse V- and V-segregates can be minimized by decreasing the solute content (P, S), decreasing Si content to prevent ascend of the interdendritic melt by buoyancy, and optimizing both the mold taper along the longitudinal direction and the aspect ratio of the mold. The occurrence of V-segregates and loose structure can be decreased by increasing the hot topping.

By carefully implementing these measures, Takenouchi of Japan Steel Works has produced 600-ton ingots with virtually no segregates or macro inclusions [4]. These ingots have been used for highly stringent applications, such as the low pressure turbine shaft and pressure vessel for an atomic reactor. In one case, seven heats of decreasing C content were poured in sequence into a 600-ton mold to dilute carbon enrichment in the hot top and in the equiaxed dendrites zone, where V-segregates should appear otherwise. Semi-empirical relationships were developed to decrease the occurrence of inverse V- and V-segregates, and these agreed well with observations. Even in such a careful casting process, however, it became mandatory to crop off the ingot bottom for macro inclusions and the ingot hot top for the solute segregation. This substantially decreased the premium yield of such ingots. Casting ingots under a vacuum in many smaller molds may not be practicable for economic reasons. In addition, the installation and dismantling of molds for ingot casting is a dusty and environmentally unfavorable operation.

Unlike ingot casting, continuous casting gives much better premium cast metal yield, when more than 3 heats are cast sequentially in one campaign. In such a sequence casting, only the very bottom and the very top of the beginning and ending portions, respectively, of each strand are discarded. Compared to normal ingot casting, continuous casting products have much better surface and internal quality, including the segregation and macro inclusions. Inverse V-segregates and V-segregates in the casting direction of continuously cast strands have been reduced to very low levels by active processing, including the following:

(1) Increasing the sedimentation of equiaxed crystals at the pool end of the strand by decreasing casting temperature, by implementing electromagnetic stirring of the melt in the mold to generate nuclei for equiaxed crystal growth, and by dispersing solute enriched melt among the boundaries of the sediment equiaxed crystals;
(2) Preventing suction of the solute rich melt from the surrounding interdendritic area into the pool end in the center of the strands. This is achieved by soft reduction of the strands at the pool end with roll pairs or an anvil pair for an optimized extent (e.g. 0.75 mm/m).

The formation of macro inclusions in continuously cast strands has also been reduced by protecting the pouring stream from air reoxidation during melt transfer from the ladle to tundish by either a long nozzle (a bell type or straight ladle shroud nozzle) or a shrouding pipe. Examples of a long nozzle and shrouded pipe are shown by Shade in Fig. 1.5 [5] and by Yamagami *et al*. in Fig. 1.6 [6], respectively.

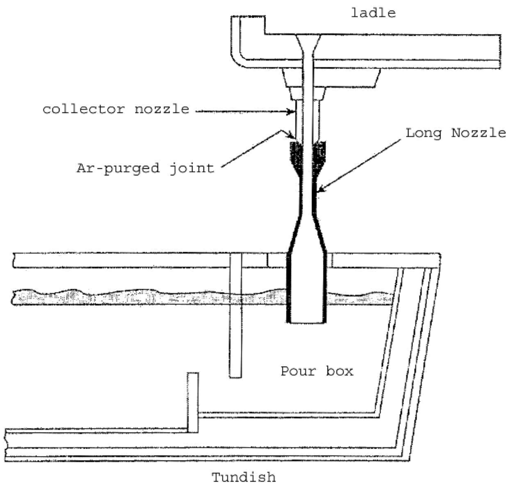


**Figure 1.5:** Tundish for casting clean steel with a long nozzle for minimum contamination by macro inclusions. [Ref. 5]

The quality of strands has improved, becoming more consistent and more controllable than ingots. Continuously cast strands (semis) are closer in shape to their final products and hence can eliminate the roughing mill in some cases. Further progress of continuous casting technology has made it possible to hot charge as-cast strands into the reheating furnace, or to hot direct roll the as-cast strands. Both techniques avoid surface conditioning, thereby reducing yield loss and earning fuel credit for reheating. Caster productivity and scheduling of casting heats have improved by not requiring surface conditioning of the cast product. Integrated efforts to cast the strands at higher withdrawal rates without compromising the cast metal quality have increased the productivity of some slab casting machines to that of the BOF levels (above 300 kt/mo/machine). In spite of large initial investments, these advantages make continuous casting the preferred solidification process over ingot casting.

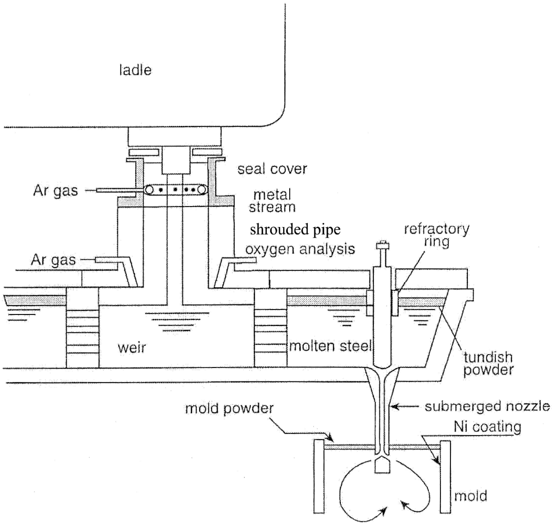


**Figure 1.6:** Tundish with a shrouded pipe and various devices that are intended to minimize contamination by and maximize flotation of macro inclusions. [Ref. 6]

## 1.2 The Role of Tundish in the Continuous Casting Process

To transfer finished steel melt from a ladle to the mold in a continuous casting machine, an intermediate vessel, called a tundish, is used. A tundish, as shown by Okimori in Fig. 1.7 [7], is a rectangular big-end-up, refractory-lined vessel, which may have a refractory-lined lid on the top. The tundish bottom has one or more nozzle port(s) with slide gate(s) or stopper rod(s) for controlling the metal flow. The vessel is often divided into two sections: an inlet section, which generally has a pour box and where steel melt is fed from the ladle; and an outlet section from which melt is fed into the mold(s). Various flow control devices, such as dams, weirs, baffles with holes, *etc.*, may be arranged along the length of the tundish. The plan view of different tundish shapes is shown by Wolf in Fig. 1.8 [8]. Dotted lines in Fig. 1.8 indicate melt path from inlet to outlet of the tundish. Longer path is preferred to prolong melt residence time to promote flotation of macro inclusions.

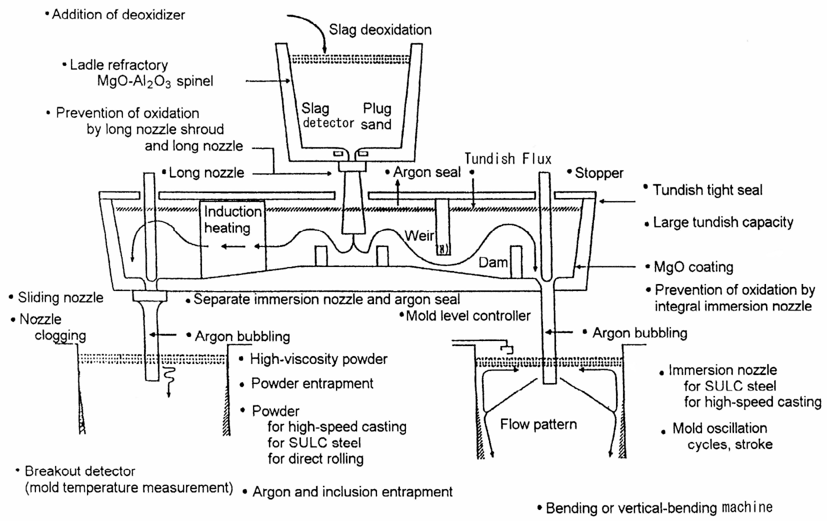


**Figure 1.7:** Continuous casting system (ladle, tundish, and molds) with all devices and precautions for casting clean steel. (SULC: Super ultra low carbon) [Ref. 7]

The tundish is intended to deliver the molten metal to the molds evenly and at a designed throughput rate and temperature without causing contamination by inclusions. The number of molds is usually 1 or 2 for a slab caster, 2 to 4 for a bloom caster, and 4 to 8 for a billet caster. The melt delivery rate into the mold is held constant by keeping the melt depth in the tundish constant. Any additional delivery rate control is exerted by the slide gates or stopper rods placed at the exit ports of the outlet compartment. The tundish acts as a reservoir during the ladle change periods and continues to supply steel melt to the mold when incoming melt is stopped, making sequential casting by a number of ladles possible. The main causes for inclusion formation and contamination of the melt include reoxidation of the melt by air and carried over oxidizing ladle slag, entrainment of tundish and ladle slag, and emulsification of these slags into the melt. These inclusions should be floated out of the melt during its flow through the tundish before being teemed into the mold.

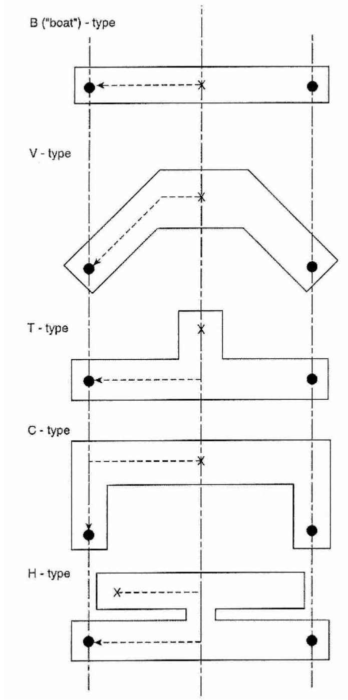


**Figure 1.8:** Plan view of different tundish shapes. [Ref. 8]

In the past, when ladle metallurgy (ex. ladle furnace, LF) was not fully developed, the tundish was expected to function as a refiner of the deoxidized melt transferred from the ladle where inclusions were not fully removed. Without LF processing, the deoxidized melt had macro inclusions and a large number of micro inclusions of indigenous origin that could agglomerate to form macro inclusions during the melt transfer. A tundish was able to reduce some fraction of macro inclusions from the melt, adjust chemical compositions, and control melt temperature to an appropriate level for feeding into the mold. With the use of the LF and/or degasser, melt cleanliness has significantly improved over the years to meet increasingly stringent customer demands, and the tundish is now seen more as a contaminator than a refiner. Appreciable contamination generally occurred during transient periods (or non steady state) of the sequential casting, i.e., during ladle opening, at the transition of two heats (or ladle change), and during ladle emptying, as shown by Tanaka *et al.* in Fig. 1.9 [9].

During transient periods, the incoming melt stream and any metal splash are heavily reoxidized by the ambient air and by the oxidizing ladle slag that is carried over into the tundish with the melt. The melt stream hits and aggressively emulsifies the ladle slag and tundish slag floating on the melt surface, which eventually get entrained into the melt. Both the reoxidation and the slag entrainment generate harmful macro oxide inclusions. The Al-deoxidized steel melt, even after removal of large particles of deoxidation product in the LF, contains a large number of suspended fine alumina particles. These particles were found to agglomerate by turbulent melt flow during the melt transfer from the ladle via the tundish to the mold, forming large alumina clusters.

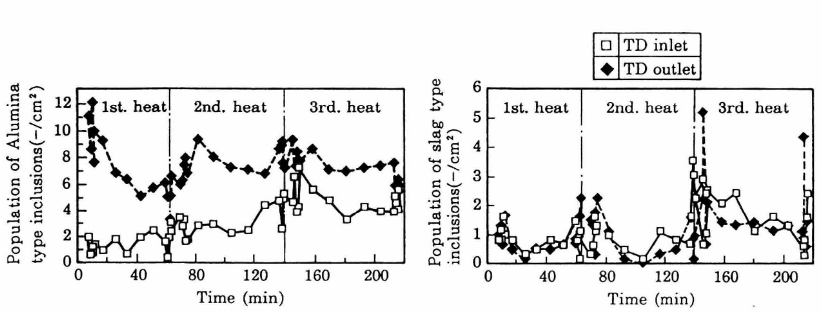


**Figure 1.9:** Alumina and slag type inclusions at the tundish inlet and outlet (Al-killed steel was poured from a 320-ton ladle with slag containing 5%FeO, into an Ar filled 60-ton tundish with MgO tundish flux). [Ref. 9]

The macro inclusions and large alumina clusters are known to be the major cause of downstream processing problems and defects occurring in strands and their final products. In industry, customers demand cleaner steel with a smaller size of macro inclusions and clusters for better performance of the steel products. Accordingly, the design and operation of a tundish must be directed toward minimizing the formation of the macro inclusions and alumina clusters, and removing them once they form. Otherwise, all the effort made in cleaning the melt in the LF and during other process steps would be of no value.

As shown in Figs. 1.5 through 1.7, various technologies such as a long nozzle or an inert gas shrouding pipe have been implemented to reduce air reoxidation and slag emulsification. Similarly, melt flow control devices have been used to enhance flotation of inclusions formed during the process. Implementation of active control of the melt temperature in a tundish has also contributed to casting clean steel. These measures have proved to be quite successful, at least during the steady state tundish operation, but may not be sufficient for the non-steady state operation, as shown in Fig. 1.9. Non-steady state operation is an integral part of long sequential casting for better metal yield. Although it is desirable to cast steel of high quality, a compromise between the quality and cost has always been struck in any tundish operation.

## 1.3 The Need for Clean Steel

The requirements for the mechanical properties and chemical composition of steel are constantly increasing, and at the same time the cost, energy, and environmental concerns in steel production are also becoming very important. Thus, the strength, ductility, durability, and corrosion resistance of steel have improved over the years to meet the need. This has been achieved partly by making steel cleaner of non-metallic inclusions, which deteriorate most of the above properties.

Non-metallic inclusions in steel are of two kinds, and each has its different mode of formation. As mentioned earlier, one is indigenous oxide inclusions which form by deoxidation of the steel melt. Most of these oxides are removed during refining and degassing of melt in the ladle, but some non-metallic oxide inclusions of small size remain suspended in the melt. The other kind is exogenous inclusions, which form by reoxidation of deoxidized steel melt by air or by the entrained slag into the melt during the melt transfer from ladle to mold. Usually, inclusions of exogenous origin are much larger than the indigenous ones, and hence are more harmful.

Inclusions cause problems during the casting, rolling, and heat treating processes and sometimes result in failure of the steel during its application. The critical size and composition of the non metallic inclusions that impair the properties of steel are not unique, but depend on the application. Generally speaking, steels with more demanding processing and applications require inclusions smaller in size and number density. Table 1.1, compiled by Emi [10] lists some examples of the critical inclusion sizes and impurity contents for high-end application steel. The critical inclusion size decreases as demands become more stringent.

Another way of reducing the harmful effects of the large inclusions is by modifying the chemical composition of inclusions to lower their melting temperature and to make the inclusions deformable during hot rolling. These large inclusions are elongated in the steel matrix as thin stringers along the rolling direction. Later, when the hot rolled steel is subjected to cold rolling, the thin stringers are broken into pieces of small size because they are brittle at cold rolling temperature. When the distance between the fragmented pieces is made greater by controlling the deformability, an undesirable large inclusion could be split into much smaller, harmless inclusions. This technology is a part of "Inclusion Engineering."

**Table 1.1:** Critical inclusion sizes and impurity contents tolerable in high performance steels.

| Application | Key property | Critical Inclusion Size (μm) | Critical Impurity Content (ppm) |
|---|---|---|---|
| DI-can sheet | Flange crack | <20 | |
| SEDDQ sheet | Average r >2.0 | | C<20, N<30 |
| Shadow mask | Blur in etching | <5 | Low S |
| Lead frame | Punch crack | <5 | |
| Sour gas pipe | HIC | Shape control | S<5 |
| LNG plate | Embrittlement | | P<30, S<10 |
| Lamellar tear | Z-crack | Shape control | *ibid* |
| Bearing, Race | Rolling-fatigue | <10 | O<10, Ti<15 |
| Case hardening | Fatigue crack | <15 | O<15, Ti<50 |
| Tire cord | Rupture | Shape control <20 | Al<10 |
| Spring wire | Fatigue crack | Shape control <20 | *ibid* |

Note – DI: Deep drawing & ironing; SEDDQ: Super extra deep drawing quality; HIC: Hydrogen induced cracking; Z-crack: Crack parallel to rolling direction.

Impurities that dissolve in the melt and form precipitates during solidification need to be minimized as well. Typical examples are phosphorus and sulfur, which form phosphides at the austenite grain boundaries and sulfides in and around the austenite grains. Since it is difficult to remove these impurities in the tundish, they should be minimized during hot metal treatment, the BOF process, and ladle furnace processing before bringing the melt to the continuous casting station.

## 1.4 Concluding Remarks

An overview of the ingot and continuous casting processes has been presented. The role and functions of the tundish in the continuous casting process and its significance in producing clean steel casting are described:

(1) The tundish links the ladle with the mold of a continuous casting machine. It accepts steel melt from a ladle and delivers it to continuous casting molds with minimum contamination, evenly and at a desired flow rate and temperature;
(2) The tundish is a refractory-lined channel consisting of an inlet and outlet sections and sometimes has flow control devices, such as dams and weirs or a baffle with holes, along its length. A tundish may have a refractory-lined lid, and has bottom ports that are assembled with slide gates or stopper rods through which the melt is teemed into the mold;
(3) Air reoxidation of the incoming steel stream is prevented with the use of a long nozzle immersed into the steel melt in the tundish or by a shrouded pipe with Ar gas flow;
(4) The long nozzle and shrouded pipe also serve to reduce emulsification of the slag into the steel melt; and
(5) Flow control devices in the tundish increase the melt residence time and help in reducing macro inclusions originating from air reoxidation and slag emulsification. At the same time, clusters of agglomerated alumina inclusions are reduced by flotation of these inclusions.

Details on these issues and topics are discussed in the following chapters.

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