Continuous Casting Produces High-Quality Steel

Approximately 90% of the steel made in the United States today is produced using the continuous casting process

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Steel production has changed dramatically in a relatively short time. This final article in a four-part series describes how slab or billet stock is produced through the continuous casting process and discusses steel quality and the inherent defects in the finished product.

Before 1970, the majority of steel produced in the United States was cast into ingots. If produced at an integrated mill, the ingots were shipped to the mill and then placed into a soaking pit where they were uniformly reheated to proper rolling temperature. After reaching the correct temperature, the ingots were rolled into billets, blooms, or slabs. This was an inefficient process because both additional labor and heat input were required. If ingots were to be shipped to a rolling mill offsite, they were slowly cooled to prevent extreme internal thermal gradients that might cause cracking. Once shipped via railcar to a rolling mill, the ingots were slowly reheated to approximately 1200°C (2200°F) before further processing. This was a tremendous expenditure of energy; therefore, a more efficient method was sought. The continuous casting process was the answer. Today, approximately 90% of the steel produced in the United States is manufactured by the continuous casting process.

Process Overview

A continuous caster may come in several different configurations. Despite minor differences, the components are relatively the same. A ladle carries molten steel to the tundish. A tundish holds molten steel for an intermediate amount of time and ensures a continuous, uniform supply to the mold. For slab casting, a tundish may serve only one mold. For smaller billet casting, several molds may be supplied from the same tundish. The tundish has several key functions that are critical to the quality of the steel produced. It is usually covered and purged with an inert gas blanket. Additionally, a light slag on the surface of the molten steel helps shield the steel from oxygen absorption. The liquid level in the tundish is kept high enough so metal flowing out the nozzle(s) does not form a vortex on the surface. A vortex may incorporate air or slag into the steel that will remain as inherent defects. Pouring nozzles located along the bottom of the tundish control the volume of flow into the casting mold. The molten steel flows out of the tundish and into the mold of the continuous caster.

Fig. 1 — This continuous steel strand is shown after its outer shell has solidified. The strand is in the process of being bent from the vertical position to horizontal by bow rolls. Notice the heavy mill scale forming on the outside of the strand.

The Mold

The mold of the continuous caster is the most important component in the process. The mold's most critical function is to extract heat from the molten steel as efficiently as possible. The mold is typically oscillated at a frequency of approximately 100 cycles per minute to prevent solidifying steel from adhering to its surface. A lubricating oil or powder is also injected along the sides of the mold to help prevent the steel from sticking. The mold forms the basic shape the metal will take. Casters may be configured to produce either billets or slabs.

The molds are made of copper and are liquid cooled. The water supplied to the mold is a critical control factor. There must be enough flow to prevent the water from evaporating upon contact with the copper. Evaporation forms a vapor barrier that severely reduces heat transfer and, therefore, should be avoided. The flow must also be sufficient to keep the interior mold face at a temperature lower than the boiling point of the lubricating oil. When the mold is in a positive cycle, the mold contacts the steel and the lubricating oil vaporizes as the molten

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Fig. 2 — Oxygen torches are shown cutting continuous cast billets to length. The billets will be sent on for further hot rolling. One tundish may supply the molten steel for multiple strands as shown in this picture.

metal and copper come in contact. On the negative cycle, the mold moves away from the steel creating a small vapor space. The oil must then cover the mold surface sufficiently before the next positive cycle occurs. The water must also keep the copper cool enough to prevent it from being permanently distorted. A distorted mold may reduce the cooling rate and distort the shape of the product. Copper with alloying elements such as silver, phosphorus, or chromium and zirconium have been shown to produce less mold distortion than pure copper.

Lubricant is supplied to the mold as a release agent. Lubricants aid in preventing such problems as shell sticking, tearing, and cracking. The oil or powder is injected into the mold through a series of nozzles. Oil has an advantage over powders; it increases the cooling rate. The oil instantly vaporizes upon contact with the steel and is broken down through a process called pyrolysis, the chemical decomposition of a substance by heat. The oil vapor increases heat transfer across the air gap left between the mold and the solidifying steel when the mold moves in its negative oscillation cycle.

The mold's oscillations affect the surface of the strand. Oscillation marks appear as a wavelike profile. Mold oscillation frequency can vary the surface from relatively smooth to rough. A rough surface increases the tendency for surface cracking, which is detrimental to the finished product. Subsequent hot or cold rolling will remove oscillation marks and provide a better surface finish.

The Steel

Steel solidifies first along the edges exposed to the mold walls. As the strand drops through the mold, the solidified walls grow in thickness. By the time the strand comes out of the mold, the four sides have coalesced, providing a form for the still liquid interior. Once out of the mold, the strand must be cooled and slowly bent from a vertical to a horizontal position — Fig. 1. The inner core will continue to cool as the strand continues out of the mold.

While the strand's interior is still molten, several undesirable factors must be considered. Alloying elements that were added to the steel may start to congregate together. A rapid cooling rate reduces the likelihood of segregation, but if cooling occurs too rapidly, cracking can occur. Additionally, slag may be entrained in the steel. Electromagnetic stirring may be used to help keep alloying elements evenly distributed and to prevent elongated dendritic growth within the still liquid core, reducing the likelihood of cracking.

Runout

As the strand continues into the runout section, water jets continue spraying it to facilitate cooling. It is vital to cool the strand to prevent a breakout — a dangerous and expensive event in which the liquid core escapes through the solidified outer shell. Escaped molten metal presents a safety concern for workers, and the casting process must be stopped. The escaped (and solidified) metal must be cleaned up and any remaining strand removed from the caster. A solid blank is then inserted into the mold to help start a new strand and the process is then restarted. In addition, cooling must occur evenly on all sides of the strand because distortion and/or cracking could occur with disproportional cooling rates.

The terminus of the continuous casting process is when an automated oxygen torch cuts the strand into smaller lengths — Fig. 2. After the continuous caster, the billet will be further processed by either hot or cold rolling.

Continuous Casting vs. Ingot Casting

There are marked improvements when continuously cast steel is compared to steel produced with the traditional ingot casting method. First, the cross-sectional area of an ingot is much larger than a strand produced by the typical continuous caster. The reduced area decreases the likelihood of cracking due to tensile stresses introduced by internal thermal gradients. Also, the reduced area implies that the cooling rate of the steel is faster. This translates to less time for segregation to occur and increases the likelihood of obtaining a more complete solid solution of alloying elements. The process is also more efficient through the elimination of cropping. Since there is no ingot, there is no need to crop. Slabs or billets leaving the continuous caster may be hot enough to be immediately sent to a rolling mill or briefly reheated to temperature after cutting to length. The continuous casting process eliminates the soaking inherent with ingots.

Inherent Defects

Inherent defects associated with continuously cast materials may be rhomboid-shaped billets or slabs, pinholes, laps, bleeds, breakouts, centerline segregations, and cracks. Cracks can be further classified as longitudinal cracks, pinch-roll cracks, centerline cracks, diagonal cracks, craze cracks, and midface cracks. The origin of each of these defects can be traced to either a mechanical or thermal source. Despite many possible types of inherent defects, steel produced today is a higher-quality product than steel produced 30 years ago.

Proper quality control checkpoints throughout the casting process minimize the likelihood of technicians finding inherent defects in the field. However, quality control programs are not perfect. Diagonal cracks, formed by the asymmetrical cooling of the strand, may make for some interesting interpretation for the nondestructive examination (NDE) technician performing longitudinal ultrasonic (UT) inspection.

Laminations are typically easy to recognize by their almost perfectly flat appearance. Similar to a lamination, a diagonal crack from a continuously cast bloom or slab will be elongated through the rolling process. A diagonal crack may at first appear to be a lamination. However, due to the angular nature of the defect, the crack will cause the UT signal to "walk" in depth and have an irregular appearance. A quick shearwave exam can be used to discriminate: a flat lamination will not return a shearwave signal, whereas a crack will return a signal when wave propagation is perpendicular to the crack.

It is not necessarily important for the NDE technician to be able to discriminate between a lamination and a billet crack. Prior to performing shearwave inspections, an exam for laminations is performed. Both of these defects will be detected if the technician performs the exam correctly. Both of these discontinuities would have to be reported as interfering conditions on the inspection report. Interfering conditions should be reported to the Level III inspector or engineer of record for evaluation. Virtually all codes do not accept cracks of any type in materials or welds.

Mill scale is inherent to any steel product that is produced at an elevated temperature. Mill scale is an oxidation product caused when heated steel is exposed to oxygen. At elevated temperatures, oxygen has an affinity for combining with iron. The mill scale forms as a thick, tough, grey/black coating on the surface of the steel. For many applications, mill scale is not detrimental to the intended application. However, it must be understood that mill scale is not part of the actual steel as a metallic bond does not exist between the steel and the scale.

For corrosion protection with some coating systems, scale may have to be removed. The National Association of Corrosion Engineers (NACE) has standards and recommendations for the inspection of surfaces prior to coating application. Typically, covered structural steel or a noncritical fabricated item does not have to be sandblasted or wheel-abraded before painting. However, to promote coating longevity in adverse industrial applications such as offshore platforms, recoating of pipelines, fuel tank relining, etc., the scale is removed. Mill scale is also an item of concern when performing International Code Council (ICC) special inspections on structural steel. It is important to remember that Class A bolted connections, such as those found on bridges, require the faying surfaces of the bolted connection to be sandblasted to bright metal prior to fitup and pretensioning.

Summary

The continuous casting process is used to produce the majority of the steel made in the United States. The process differs from traditional ingot casting in several ways: it is more energy efficient, requires less labor, and eliminates some inherent defects of the ingot casting process. However, no process is perfect. Continuous casting also has inherent discontinuities that may affect the final acceptance of the steel for its intended application. As a whole, steel produced by the continuous casting process is higher in quality and possesses better mechanical properties than steel produced thirty years ago.❖

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