Continuous Casting (metallurgy)

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Continuous casting is used to mass produce basic metals into long, semi-finished shapes with constant cross section, which are later processed into over 800 million tons of steel, 20 million tons of aluminum, and 1 million tons of copper, nickel, and other metal products in the world each year. Cross-sections can be rectangular, for later rolling into plate or sheet, square for long products, circular for wire and seamless pipes, "dog-bone" shapes for "I" or "H" beams, and even thin strip, rod, and other products. Continuous casting is distinguished from other solidification processes by its "steady state" appearance. That is, the molten metal freezes against the mold walls and is withdrawn from the bottom of the mold at a rate which keeps the solid / liquid interface at a constant position with time, relative to an outside observer. The process works best when all of its aspects operate in this manner.

Continuous casting is the most efficient way to solidify large volumes of metal into simple shapes with consistent quality. It has been steadily replacing older ingot casting processes since it was developed in the 1950's and 60's. Compared with other casting processes, continuous casting generally has a higher capital cost, but lower operating cost. It produces "near-net shapes" that are closer to the final product shape, so require less subsequent deformation. This makes continuous casting more energy- and cost- efficient than alternative processes.

Several different types of commercial continuous casting processes exist (**Fig. 1**). Vertical machines cast aluminum and a few special alloys. Curved machines are used for steel, which can tolerate some bending and / or unbending of the solidifying strand. Short horizontal casters are sometimes used, to reduce machine height. Finally, thin-strip casting is being pioneered for steel and other metals to minimize the amount of rolling required.

Steel Continuous Casting. Recent innovations have transformed the continuous casting of steel into a sophisticated, high-technology process, that makes 90% of steel in the world today. In the curved machine process (**Fig. 1, center**), 50-200 ton ladles of molten steel are supplied periodically to the caster from the steelmaking process. A hole in the bottom of the ladle is opened to pour steel into a large, bath-tub shaped vessel, called a "tundish". The tundish holds enough metal to provide a continuous flow to the mold, even while exchanging ladles. The tundish can also serve as a refining vessel to float detrimental inclusions (foreign solid particles composed of brittle oxides) to the top surface. There, they are absorbed into the "slag layer", which is a thin covering of molten glass that floats on the liquid metal surface and is later discarded. Any inclusions that remain in the product may form surface defects during subsequent rolling operations such as "slivers" (ugly longitudinal streaks) that sometimes delaminate into loosely attached strips or blisters. Large inclusions also cause local internal stress concentration, which lowers the steel strength and "fatigue life" (how many loading cycles can be endured before a part fails in service). To produce higher quality product, the liquid steel must be protected from exposure to air by the slag layer that covers each steelmaking vessel and by using ceramic nozzles between vessels. If not, then oxygen in the air will react to form detrimental oxide inclusions in the steel.

A close-up of the mold region shows important phenomena in the continuous casting process (**Fig. 2**). Molten steel freezes against the water-cooled walls of a bottomless copper mold to form a solid shell. The mold is oscillated vertically in order to discourage sticking of the shell to the mold walls. Drive rolls lower in the machine continuously withdraw the shell from the mold at a rate or “casting speed” that matches the flow of incoming metal, so the process ideally runs in steady state. The liquid flow rate is controlled by restricting the opening in the nozzle according to the signal fed back from a level sensor in the mold.

The most critical part of the process is the meniscus, found at the junction where the top of the solidifying shell meets the mold and the liquid surface. This is where the surface of the final product is created. Defects such as surface cracks can form here, if problems such as level fluctuations occur. To avoid this, oil or mold slag is added on top of the steel meniscus, which then flows into the gap between the mold and shell. In addition to lubricating the contact, an optimized mold slag layer protects the steel from air, provides thermal insulation, and absorbs inclusions. It is also important to control flow across the top surface. Excessive speed can entrain mold slag, which is later trapped as inclusions, while stagnant conditions cause surface depressions and related defects.

Below mold exit, the thin solidified shell (6-20 mm thick) acts as a container to support the remaining liquid, which makes up the interior of the strand. Water or air mist sprays cool the surface of the strand between the support rolls. The spray flow rates are adjusted to control the strand surface temperature with minimal reheating until the molten core is solid. After the center is completely solid (at the “metallurgical length” of the caster, which is 10 - 40m from the top of the mold) the strand is cut with oxyacetylene torches into slabs or billets of any desired length.

Different continuous casting machines cast cross sections of various shapes and sizes. Heavy, four-piece plate molds with rigid backing plates are used to cast large, rectangular “slabs”, (50-250 mm thick and 0.5–2.2 m wide), which are rolled into a plate or sheet. A recent trend in the steel industry is the increased use of thin-slab casting (50-100mm thick), which needs much less rolling to make sheet product than with conventional thick-slab casting, (150-250mm thick). Since it was first commercialized by Nucor in Crawfordsville, Indiana in 1985, thin slab casting has grown to over 16 million tons of annual capacity - almost 20% of the United States market - and is still growing. Similar molds are used to cast relatively square “blooms”, which range up to 400 x 600 mm in cross section. Single-piece tube molds are used to cast smaller “billets” (100 - 200 mm thick) which are rolled into long products, such as bars, angles, rails, nails, and axles. The new strip casting process is being developed using large rotating rolls as the mold walls to solidify an ultrathin 1-3mm thick steel sheet directly from the liquid. This revolutionary new technology is nearing full commercialization and will likely compete in the steel marketplace in the a few years.

When casting large cross sections, such as slabs, a series of rolls must support the soft steel shell between mold exit and the metallurgical length, in order to minimize bulging due to the internal liquid pressure. Extra rolls are needed to force the strand to “unbend” through the transition from the curved to the straight portion of the path shown in Fig. 1. If the roll support and alignment are not sufficient, internal cracks and segregation may result.

The process is started by plugging the bottom of the mold with a “dummy bar”. After enough metal has solidified above it (a process similar to conventional casting), the dummy bar is slowly withdrawn down through the continuous casting machine and steady-state conditions evolve. The process then operates continuously for a period of one hour to several weeks, when the molten steel supply is stopped and the process must be restarted. The maximum casting speed of 1-8 m/min is governed by the allowable length of the liquid core, and to avoid quality problems, which are generally worse at higher speeds.

After the steel leaves the caster, it is reheated to a uniform temperature and rolled into sheet, bars, rails, and other shapes. Modern steel plants position the rolling operations close to the caster to save on reheating energy.

Vertical Semi-Continuous Casting. Most commercial nonferrous alloys are cast by semi-continuous vertical casting machines, (**Fig. 1**) typically as 0.05 - 0.5m diameter round sections called “ingots” for subsequent extrusion, forging or rolling. This process differs from steel continuous casting in that it must be stopped periodically to remove the cast ingot. Other differences are the slower casting speed, (0.03 – 0.1 m/min.) which is needed to avoid internal cracks, and makes the metallurgical length shorter.

The two most common casting processes for aluminum are the direct-chill (DC) and electromagnetic (EM) processes, which differ in how the liquid is supported at the meniscus. The DC process (Fig. 1 left) uses water-cooled mold walls, similar to steel casting, while the EM process induces horizontal electromagnetic forces to suspend the metal from ever touching the mold walls. In both processes, the solid metal surface shrinks away from the mold walls shortly below the meniscus and is cooled with spray water.

Other Continuous Casters. Many other continuous casting processes exist for special applications. Electroslag remelting (ESR) and vacuum arc remelting (VAR) are two forms of vertical continuous casting used for nonferrous metals, superalloys and specialty alloy sections up to 1.5m diameter. Heat is supplied from an electrode above the melt and the top surface is protected from air reoxidation with a thick slag layer (ESR) or a vacuum (VAR). These processes remove impurities such as sulfur to produce highly refined metal with less segregation and fewer other defects than found in conventional continuous casting. Their products are more costly, but are needed for critical parts such as found in the aerospace industry.

Challenges. Understanding and controlling the casting process is important because it may introduce defects that persist into the final product, even after many later processing steps. These defects include oxide inclusions, porosity, segregation, and cracks. In addition to expensive plant experiments, understanding comes from physical water models and advanced computational models. Water flows in a similar manner to steel, so scale water models can visualize the flow, especially with the aid of recent tools such as particle image velocimetry. Helped by recent improvements in computer power and software, computational models can simulate phenomena ranging from metallurgical thermodynamics to fluid flow, heat transfer, solidification and stress generation. This knowledge is used in designing features such as the nozzle and mold shapes. In addition, online models control the liquid steel and cooling water flows, casting speed and other parameters. Improvements to continuous casting must be cost efficient, owing to economic pressure from the general oversupply of primary metals in the world. Future advances likely will rely on even better models and control systems.

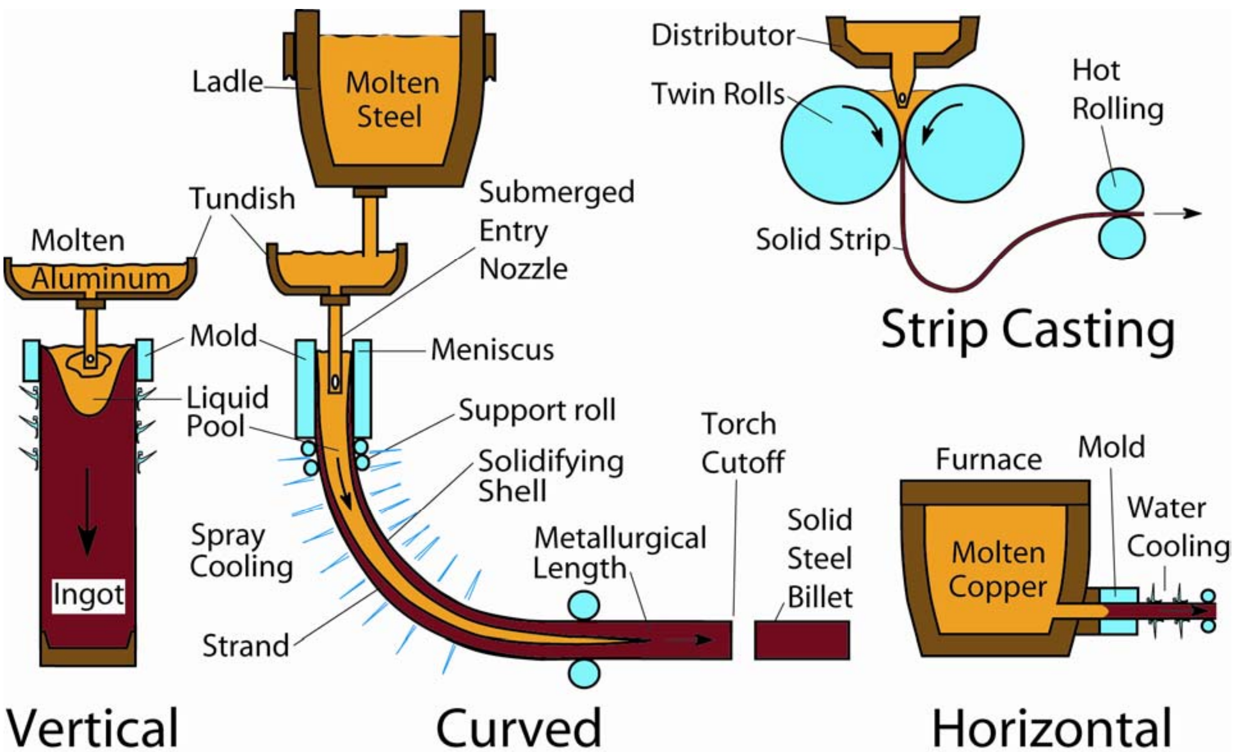

Figure 1. Various continuous casting processes

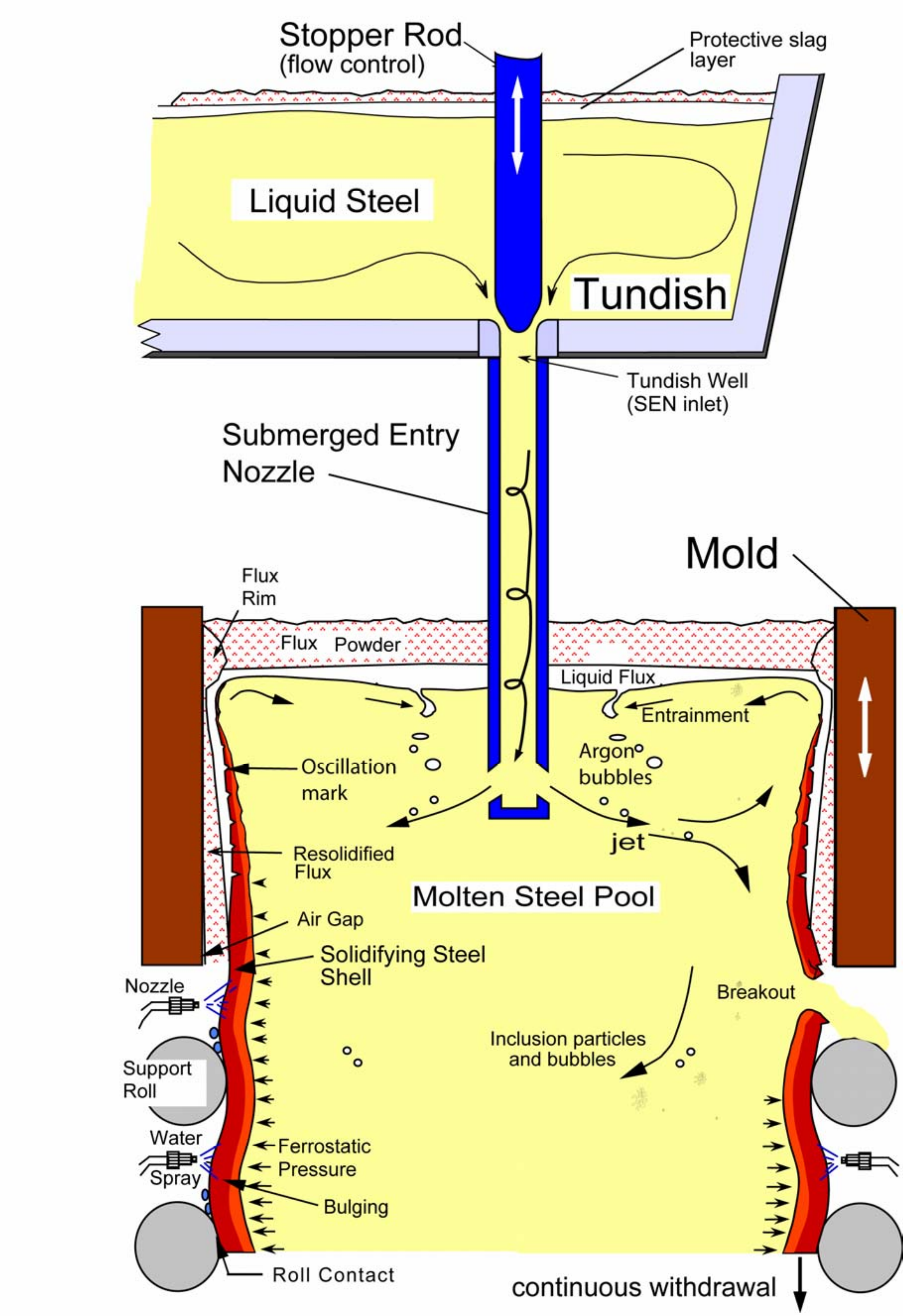

Figure 2. Schematic of mold region of continuous casting process for steel slabs

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Key terms:

Casting speed, Tundish, Mold, Strand, Billet, Metallurgical length, Spray cooling, steel, aluminum, meniscus, inclusions