Introduction

Continuous casting of stainless steel is the process by which molten stainless steel is solidified and formed into a slab, billet, or bloom, which are various shapes. It is an integral part of the production of the more than 40,000 metric tons produced annually. Up until the commercial introduction of continuous casting, stainless steel was poured or teemed into ingot molds. In present day production, ingot teeming is still used but at a premium cost of production and often for lower volume or more specialized alloys. Continuous casting has improved yield, quality, productivity and cost efficiency relative to ingot teeming production.

Continuous casting of stainless steel allows molten metal from a ladle, which is used to transfer molten metal throughout a melt shop, to flow into a tundish and then into a water-cooled copper mold where the molten metal forms a solid shell and then continues to solidify while going down the machine through various segments. The solid metal strand after becoming completely solidified is then cut into segments or slabs. Understanding the history of teeming and continuous casting as well as some of the current industry practices will allow for a better understanding of the use of stainless steel in the numerous applications.

History and Description of Ingot Teeming

Ingot teeming has existed in some form or fashion for centuries with the simple example of gold and silver being poured into bars that were often used as currency. Once stainless was invented in the early 1900s, the process by which it was solidified initially was by pouring into molds. In literature, casting and teeming is often used interchangeably, but to distinguish between the two terms, the continuous dynamic producing of stainless steel will be referred to.
as continuous casting or casting. The discreet and stationary pouring of stainless steel into ingots will be referred to as teeming or ingot pouring.

Ingot teeming is simply pouring molten metal into cast iron molds. Initially metal was poured into the top of the mold, but the top pouring of stainless steel was replaced by bottom pouring of ingots. Figure 1 illustrates the difference between bottom pouring and top pouring. Top pouring was essentially having the stream of molten metal go directly into the top of the mold as if you were filling up a large ice cube tray. This caused lots of wear and erosion on the mold as the molten metal directly impacted the bottom of the mold. Relative to bottom pouring, the quality is also much poorer with top pouring. This poor quality is because the molten metal is exposed to the open air for much longer which introduces oxygen. Also, the top of the molten metal experiences turbulence as molten metal continually hits the top surface of the molten ingot as it rises during teeming. Any turbulence in either casting or teeming leads to poorer quality by allowing for voids, cracks, or rough surface to form. There is also significant variation ingot to ingot because each one is poured individually. The last ingot poured has cooler molten metal and much less head pressure in the ladle.

Bottom pouring of ingots which is still used in industry, has the molten metal poured into a trumpet or center riser which through a ceramic tunnel feeds the molten metal into multiple molds simultaneously. The exposure to air and oxygen, turbulence, mold to mold variation is reduced greatly. In all teeming, fluxes and powders are added to provide lubrication between the surface of the mold and the molten metal. Exothermic powders or boards are also added to the top of an ingot that is exposed to air to insulate the top of the...
ingot so that it cools at a rate closer to the rest of the ingot and reduce cavities and warping, known as hot top.

Ingot molds come in a variety of sizes and shapes depending on the alloy and downstream application. Ingots also come in a variety of weights from a few hundred pounds up to 20,000 pounds or more. After the ingots are cooled, they are stripped out of the molds which typically is done with a crane with a special attachment to push or plunge the ingot out of the mold. Ingots are then reheated and processed or remelted and further refined for downstream processing.

![Figure 1 - Ingot Teeming Diagram - Bottom Pouring (left), Top Pouring (right)]

**History of Continuous Casting Stainless Steel:**

The idea of continuous casting can be traced back to the 1800s to patents by J Laing and Henry Bessemer, however the practice of continuous casting in mass production didn’t begin until the 1950s. The key developments that allowed for realization of the initial concepts of continuous casting came from many different people

Key developments:

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• Bessemer implemented a tundish (holding container between ladle and mold) with stopper for slag retention and precursor of a dummy bar to keep molten metal in mold at startup

• Goeran Fredrik Goeransson introduced a stoppered ladle for the transfer of liquid steel (1858)

• Henry Bessemer invented the initial lade turret to swing the ladle into place (1859)

• David D Lewis invented the first ladle slide gate (1885)

• Benjamin Atha patented a water cooled, bottomless mold and a dummy bar featuring a claw shaped head to extract the initial metal billet (1886)

• Arthur McKee Co. built one of the first casters designed by John T Rowley with the ability to bend and straighten the billet (1915)

• Cornelius W. van Ranst patented the concept to reciprocate up and down to reduce friction in the mold (1921)

• Siegfried Junghans of Germany developed mold oscillation and rudimentary mold level control

• The first CC machine for non-ferrous metal was installed by Rossi at Scovill Manufacturing Co. (1937)

• Edward R. Williams created at Republic Steel for billets and mini slabs (1942) and later another pilot unit with automatic mold level control at Babcock and Wilcox (1948)

The first commercial caster was designed by Rossi and built by Koppers Co. and was installed at Allegheny Ludlum in 1949. The machine cast round 150 mm diameter billets and mini slabs 75
mm x 380mm. Some of the modern features already developed for this machine are inert gas shrouding of tundish and mold, preheating of the pouring nozzle.

**Modern Day Continuous Casting:**

Continuous casting can typically be broken up into the following sections: machine setup, start of cast, steady state casting, ladle transition, end of cast. To better understand the equipment and layout of a continuous caster, please reference Figure 2. During the machine setup phase, all of the spray cooling is checked and the mold is packed or prepared for the start of cast. To pack the mold, a dummy bar is sent up through the caster machine through all the segments. The dummy bar holds the molten metal in the mold until the initial solidification can take place and then moves down the casting machine segments with the slab until disconnecting just before the torch. Once the dummy bar is in place, the mold is lubricated with a specialized oil and the joint of the dummy bar and mold is caulked and chill scrap is poured in to the mold to absorb the heat of the molten metal at the start of the cast. This is a very critical step, because if a mold is improperly packed, there is a high likelihood of a caster breakout. By the time the metal strand leaves the mold, a shell is formed and no molten metal is exposed. If for some reason, molten metal is exposed, this is called a caster breakout. When molten metal gets into the segments and rolls, the caster may have to shut down for hours or even days for repairs. The tundish is prepped in a separate area by spraying refractory material that is then baked until dry. This refractory lining protects and insulates the tundish from the molten metal during casting. If a tundish is to be used for multiple ladles in sequence casting, then a thicker layer of refractory material is sprayed on. The tundish is what holds the molten metal from the ladle before flowing into the mold. The main function of the tundish is to
reduce turbulence and vortexing. Various often proprietary hardware such as dams and weirs are installed in the tundish as well as the submerged entry nozzle (SEN) after the refractory material has been cured. The submerged entry nozzle is the tube at the bottom of the tundish that is lowered into the mold. A stopper rod inside the tundish controls the flow of metal from the tundish to the submerged entry nozzle. The submerged entry is preheated to prevent thermal shock when molten metal flows through it for the first time. The hardware for the stopper rod is installed. The specified tundish fluxes and mold powders and put into place during the setup phase.

Once the caster setup phase is complete, the start of cast phase begins. The molten steel arrives in the ladle from the ladle stir station where the caster ready temperature and final chemistry requirements are achieved. The ladle is typically put on a turret which spins the ladle into place. The turret allows for multiple ladles or batches of steel to be cast continuously without ending the cast and having to start a new cast. After the ladle is in place and the tundish and SEN are lowered into the mold, a shroud is attached to the ladle nozzle. The purpose of the ladle shroud is to prevent the molten metal being exposed to open air where it could be oxidized. The shroud is flushed by an inert gas, typically argon. The ladle is opened and the tundish begins to be filled. Once the tundish is filled with enough volume to submerge the ladle shroud and for the turbulence of the ladle open to calm down, the stopper rod is opened and the mold begins to be filled. The mold is filled at a rate which allows the molten metal to solidify and form a shell as it comes in contact with the water-cooled copper mold. As the mold level comes up from the bottom of the mold where the dummy bar is packed to the level at which the SEN is submerged, then the caster machine is turned on and mold powder is
added to lubricate the surface of the mold in contact with the molten metal. The mold also begins to oscillate up and down to prevent the metal from sticking to the mold. Once the machine is turned on, the dummy bar begins to move down the machine allowing for metal to be begin to be withdrawn from both the tundish and the mold. Flux is thrown on the metal in the tundish to insulate the heat and create a protective layer between the molten metal and air. One of the common upset conditions that can occur during startup is when a ladle doesn’t free-open. If the slide gate is opened to fill the tundish and no molten metal comes out, then the nozzle of the ladle is burned open with an oxygen lance. Once open the tundish is filled and the slide gate is closed momentarily for the shroud to be reattached and then once open, normal casting and startup resumes.

*Figure 2 - Continuous Casting diagram showing molten and solidified metal*
After the cast has been started, the steady state casting phase begins. The slide gate controls the flow of metal from the ladle into the tundish. In the steady state casting phase, the slide gate is controlled hydraulically to maintain a consistent weight of molten metal in the tundish. The mold level is also controlled automatically by the use of an electro-magnetic sensor that controls stopper rod. The stopper rod will raise open creating a bigger opening allowing mold level to be increase the layer of the mold level or be lowered to reduce opening and decrease the height of the mold level. Mold level is one of the key indicators of slab surface quality and with automatic control can be maintained at a set point +/- 20 mm. During steady state casting, mold powder and tundish flux are continually applied to both the mold and tundish by each of the operators. For the mold, powder is applied to keep the mold “dark” meaning that you don’t want glowing molten metal to be seen. Throughout casting, the mold powder is melting at the meniscus (surface of molten metal in the mold) and lubricating down the side of the mold. Typically, final chemistry samples are taken out of the tundish, unless it’s specified to be taken upstream. Temperature samples are taken out of the tundish as well and the temperature of the metal will dictate per the standard operating procedure what speed the caster should run at. The higher the temperature, the slower the speed to allow the shell to properly form in the mold and the slab to solidify lower down in the machine. If the temperature is colder, than the caster will be run at a higher speed to keep the metal strand moving. If it cools too much, it may begin to expand or get stuck in the machine. A caster will have a maximum speed that cannot be exceeded, regardless of the temperature of the ladle. If a ladle is too cold, it will be revessled back into the AOD (argon oxygen decarburization) to be
heated up. As the slab moves down the machine, it is sprayed continually with water to cool the slab and aid in the solidification process and the slab also moves down a series of rolls that help the slab maintain the proper thickness and as the slab moves further down the width of the metal strand decreases as the rolls compress it while the center is still molten. During steady state casting, with much of the machine running in automatic, the issues that arise are infrequent.

The weight of metal in a ladle is known, and with the weight, an estimated strand length is calculated. As that length nears its end, meaning the metal in the ladle is running out, one of two things can happen, the cast can end with one ladle or it can be sequenced with additional ladles of the same grade. This is determined beforehand as the weekly schedule is set. If a sequence is scheduled, the next ladle is placed on the turret which can hold two ladles. The ladle that is nearly empty is shut off either when slag (the less dense oxide layer that floats on top of the metal in the ladle) is detected visually by operators or detected by a sensor that can differentiate between metal and slag, or at a pre-determined strand length. After the ladle is shut off the cast continues while draining the molten metal built up in the tundish. Once all hydraulic hoses and shrouds are disconnected from the ladle, the turret is rotated bringing the full ladle into position, at which point the shroud and hydraulic hoses are reconnected and the slide gate is opened allowing metal to flow from the new full ladle into the tundish. During the ladle transition, the speed of the caster may be reduced to not drain the tundish too quickly depending on the size of the tundish. Once the tundish weight is back at the target level, the automatic control of the slide gate is resumed and steady state casting continues.
If the ladle is the last of a sequence or is being cast as a single, then the end of cast or capping off procedures are followed. Similar to a ladle transition as a ladle is close to emptying, operators turn off the automatic weight control for the tundish and begin to control the slide gate manually. As soon as slag is detected, the slide gate is closed cutting off the metal flow from the ladle. After the hydraulic hoses are disconnected from the ladle, the ladle is moved by rotating the turret. The tundish is drained and when it is determined either by weight or visual inspection that most of the metal in the tundish has been cast, then the stopper rod is closed manually. It’s critical that no slag is drained from the tundish, because this could prevent a good cap-off. The cap-off procedure occurs by allowing most of the powder to be burned off the meniscus. Once the tundish stopper rod is shut off, then the tundish is raised and moved out of the way and the operators begin applying water to the top of the strand in the metal to cap-off or harden the end of the strand so that no molten metal will be exposed to the rolls and segments beneath the mold. The machine is stopped temporarily during the cap-off procedure. Once the end of the strand is solidified, the machine is started again and the strand continues to move. Throughout the cast the strand is straightened at the end of the radius through a series of rolls and then cut by a torch into ordered slab, billet, or bloom lengths.
References


Note: The author previously worked at ATI Flat Rolled Products (formerly Allegheny Ludlum) and has worked as an operator at each of 7 positions at a continuous caster and ingot teeming during a lockout with the union