# Lecture 33 continuous casting of steel

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**Keywords:** continuous casting, tundish metallurgy, secondary cooling, defects in cast product

## Introduction

In the continuous casting, molten steel is poured from the tundish in the water cooled mold and partially solidified bloom/billet or slab (hereafter called strand) is withdrawn from the bottom of the mold into water spray so that solidified bloom/billet or slab is produced constantly and continuously. Continuous casting is widely adopted by steelmakers. The advantages of continuous casting over ingot casting are

- Quality of the cast product is better
- No need to have slabbing/blooming or billet mill as required when ingot casting is used.
- Higher extent of automation is possible
- Width of the slab can be adjusted with the downstream strip mill.
- Continuously cast products show less segregation.
- Hot direct charging of the cast product for rolling is possible which leads to energy saving.

## How casting is done continuously?

The essential components of a continuous casting machine are tundish, water cooled mold, water spray and torch cutters. Tundish, mold and water spray are arranged such that molten stream is poured from tundish to mold and solidified strand (billet/bloom/billet) is produced continuously. The required length of the strand is cut by torch cutter. In figure 32.1, the arrangement of tundish, mold and water spray is shown.

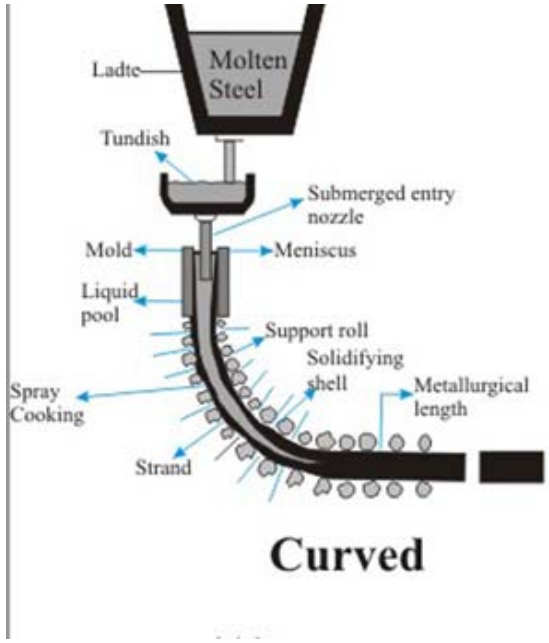


**Figure 33.1 Arrangement of tundish, mold and water spray in a curved mold machine (paste figure 2.3a)**

*Tundish*

Tundish is a refractory lined vessel. Liquid steel is usually tapped from ladle into tundish. The stream is shrouded as it enters  from ladle to tundish. The functions of the tundish are:

**Reservoir of molten steel**

Tundish acts as a reservoir for molten steel. It supplies molten steel in presence of a slag cover to all continuous casting molds constantly and continuously at constant steel flow rate. The flow rate is maintained constant by maintaining a constant steel bath height in the tundish through teeming of molten steel from the ladle. The number of mold is either one or more than one. Normally bloom and billet casting machines are multi-strand i.e. number of molds are either 4 or 6 or 8. Slab casters usually have either single or two molds. During sequence casting and ladle change- over periods, tundish supplies molten steel to the molds.

*Distributor*

Tundish distributes molten steel to different molds of the continuous casting machine at constant flow rant and superheat which is required for stand similarly with reference to solidification microstructure. Control of superheat is required in all the moulds to reduce break-out. Location of ladles stream in the tundish is important. It may be located symmetric or asymmetric to the centre of the tundish depending on the number of mold. For single strand machines, molten stream enters from one side and exits the other side of the tundish. In multi-strand tundishes, ladle stream is either at the centre of the tundish or displaced to the width side of the tundish.

*Inclusion removal*

Tundish helps to remove inclusions during the process of continuous casting. For this purpose liquid steel flow in the tundish is modified by inserting dams, weirs, slotted dams etc. The whole idea is to utilize the residence time available before steel leaves the tundish. For example, if capacity of tundish is 40 tons and casting speed is 5 tons/min, then the average residence time of molten steel in the tundish is 8 minutes. During this average residence time., inclusion removal can be exercised .For this purpose flow of steel melt in the tundish has to be modified so as to accelerate the inclusion removal. The Inclusion removal is a two step step unit operation, namely floatation and absorption by a flux added on the surface of the tundish. Flux is usually rice husk, or fly ash or some synthetic powder. The readers may see the references given at the end of this lecture for further reading.

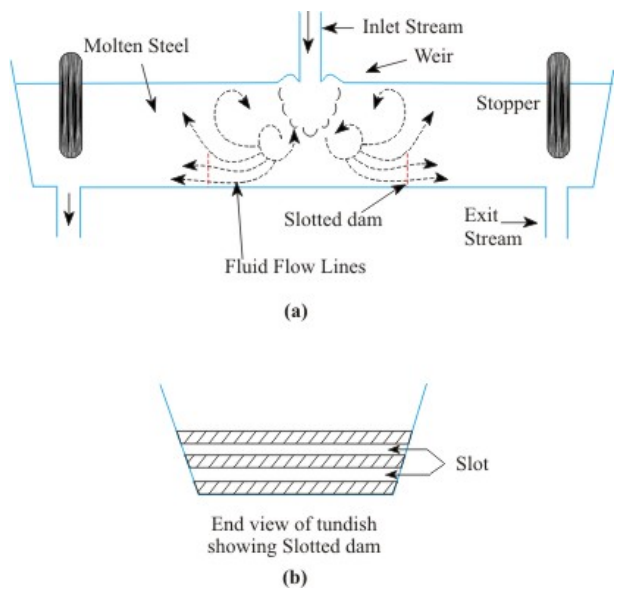


Figure 33.2: Tundish with flow control device, namely weir and slotted dam

**Mold:**

Mold is the heart of continuous casting. In the water cooled mold, molten stream enters from the tundish into mold in presence of flux through the submerged nozzle immersed in the liquid steel.

Solidification of steel begins in the mold. The casting powder is added onto the top of molten steel in the mold. It melts and penetrates between the surface of mold and the solidifying strand to minimize friction as shown in figure 33.2. Control of height of molten steel in the mould is crucial for the success of the continuous casting machine. The solidification begins from the meniscus of steel level in the mould. Mold level sensors are used to control the meniscus level in the mould.

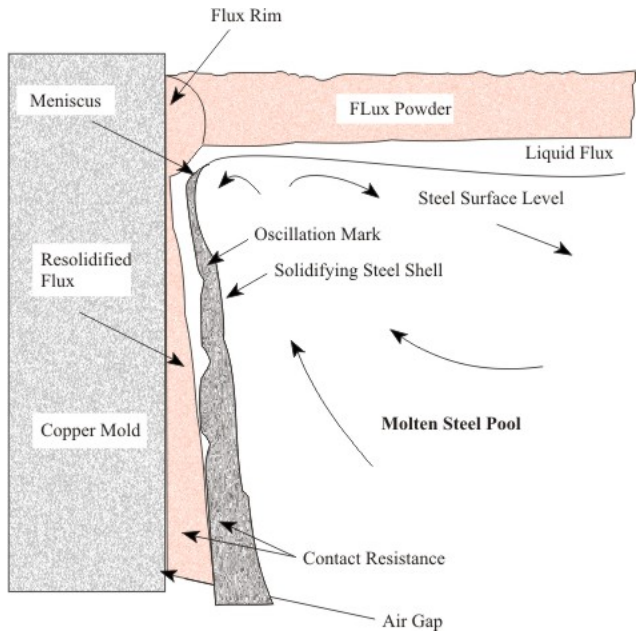


Figure 33.2: Role of flux in continuous casting mold

As seen in the figure, flux melts and enters into the gap between mold surface and solidified strand. Molds are made of copper alloys. Small amounts of alloying elements are added to increase the strength. Mold is tapered to reduce the air gap formation. Taper is typically 1% of the mold length. For $100\text{mm} \times 100\text{mm}$ cross section of mold the taper is about 1mm for 1m long mold. The cross section of the mold is the cross section of the slab/bloom/billet. Length of the mold is around $0.75 - 1.4\text{m}$ and is more for large cross sections. Mold cross section decreases gradually from top to bottom. Mould extracts around 10% of the total heat.

The mold is oscillated up and down to withdraw the partially solidified strand (strand is either billet or bloom or slab).The oscillated frequency can be varied. At Tata steel slab caster frequency is varied in between 0 and 250cycles/min and the stroke length from 0 to 12mm.

Steel level in mould is controlled, that is the meniscus for smooth caster operation. Sensors are used to control the meniscus level.

The functions of mold flux are.

- Inclusion absorption capability.
- Prevention of oxidation.
- Minimization of heat losses.
- Flux on melting enters into the air gap and provides lubrication.

For the above functions the flux should have the following properties.

- Low viscosity
- Low liquidus temperature
- Melting rate of flux must match with the speed of the continuous casting.

Mass flow rate of flux can be calculated by

$$\dot{m} = \rho\left(\frac{U_s\delta}{2} + \frac{\rho\, g\delta^3}{12\mu}\right)$$

$\dot{m} =$ Powder feed rate $\mathrm{kg/sm}$, $U_s$ casting speed $\mathrm{m/s}$, $\delta$ is boundary layer thickness, $\rho$ is density of flux, $\mu$ is viscosity of slag $(\mathrm{kg/ms})$.

Consider slab casting speed $0.05\mathrm{ms}^{-1}, \mu = 3 \times 10^{-1}\frac{\mathrm{kg}}{\mathrm{ms}}, \delta = 0.1\mathrm{mm}, \rho = 3000\mathrm{kgm}^{-3}$

$$\dot{m} = 0.1\frac{\mathrm{kg}}{\mathrm{sm}}$$

For a mold of length $1\mathrm{m}, \dot{m} = 6\ \mathrm{kg/min}$

Typically the range of composition for mold fluxes are.

| | | | | | |
|---|---|---|---|---|---|
| CaO | 25-45% | $Na_2O$ | 1-20% | BaO | 0-10% |
| $SiO_2$ | 20-50% | $K_2O$ | 1-5% | $Li_2O$ | 0-4% |
| $Al_2O_3$ | 0-10% | FeO | 0-6% | $B_2O_3$ | 0-10% |
| $TiO_2$ | 0-5% | MgO | 0-10% | F | 4-10% |
| C | 1-25% | MnO | 0-10% | | |

**Design of Mold flux**

There are specific requirements of mould flux for specific grade of steel. For example,low carbon aluminum killed steel requires flux which can absorb $Al_2O_3$ inclusion without an adverse effect on viscosity. A lower viscosity helps the flux provide sufficient lubrication at higher casting speed.

Medium carbon grades $(0.08\%\ \mathrm{C}$ to $0.18\%)$ are prone to cracking. High solidification temperature of flux reduces heat through mold. For adequate lubrication low viscosity of the flux is required.

High carbon grades too require flux of low viscosity and melting point.

Ultra low carbon steels ($C < 0.005\ \%$) requires flux which can absorb non metallic inclusions, improve insulation, provided good lubrication, stable properties and minimal slag entrapment.

Table gives effect of chemical composition on mold flux properties.

| Increase in | Viscosity | solidification temperature | Melting point |
|---|---|---|---|
| CaO | Decrease | Increase | Increase |
| $SiO_2$ | Increase | Decrease | Decrease |
| $CaO/SiO_2$ | Decrease | Increase | Increase |
| $Al_2O_3$ | Increase | Decrease | Increase |
| $Na_2O$ | Decrease | Decrease | Decrease |
| F | Decrease | Increase | Decrease |
| $Fe_2O_3$ | Decrease | Decrease | Decrease |
| MnO | Decrease | Decrease | Decrease |
| MgO | Decrease | Decrease | Decrease |
| $B_2O_3$ | Decrease | Decrease | Decrease |
| BaO | Decrease | Decrease | Decrease |
| $Li_2O$ | Decrease | Decrease | Decrease |
| $TiO_2$ | No change | Increase | Increase |
| $K_2O$ | Decrease | Decrease | Decrease |

The table can be read as for example increase in CaO decreases viscosity but increases solidification and melting temperature of the flux. Similarly the effects on other constituents on the viscosity and solidification/melting temperature can be understood.

**Secondary cooling**

Below the mold partially solidification strand is water sprayed to complete the solidification. Number of primary parameters which influence the rate of heat extraction are.

- Water drop flux
- Mean drop size
- Droplet velocity hitting the strand surface
- Wetting effects.

Spray cooling essentially involves boiling heat transfer. A water vapour blanket forms on the strand surface which prevents direct contact of water droplets with the strand surface. Velocity of droplets should be such that droplet can penetrate the vapour layer so that droplets can wet the surface and cools the surface.

In secondary cooling, number of nozzles is distributed over the surface of the moving strand. Overlapping of spray may occur. Distance between nozzles is important.

**Heat transfer in continuous casting**

Heat transfer in continuous casting takes place in mold and in secondary cooling by a combination of conduction, convection and radiation. Figure 33.3 shows heat transfer in the mold and secondary cooling.

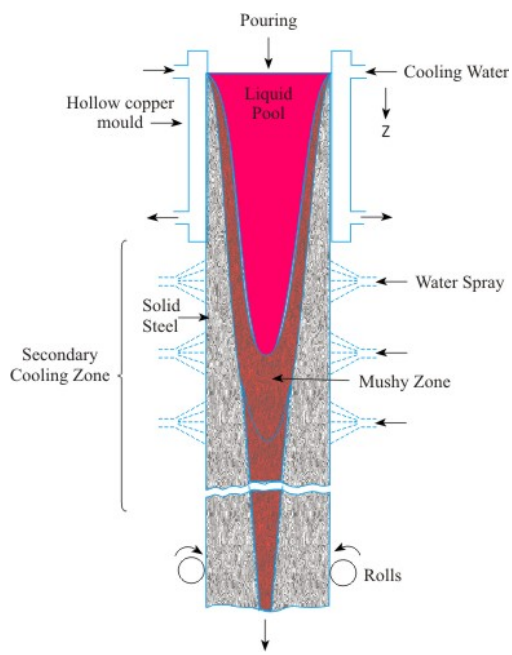


**Figure 33.3: Heat transfer in the mold and secondary cooling zone and the formation of solid shell. Mushy zone and liquid core can also be seen**

In the mold air gap formation influences heat transfer. The higher heat flux in mould can lead to higher casting speeds. Heat flux depends on.

- Composition of steel.
- Mould taper.
- Type of lubricant
- Type of mould straight or curve
- Casting speed.

The major requirements for secondary cooling

- Partially solidified strand must have shell sufficiently strong at the exit of the mold to avoid breakout due to liquid pressure.
- The liquid core should be bowl shaped
- Solidification must complete before the withdrawl roll.

Casting speed i.e. rate of linear movement of strand/ minute from the mould is important. Casting speed must match with the rate of solidification. Slabs are cast within the speed ranging from 1.5/min to 2.5m/min.

The intensity of heat extraction by water spray in secondary cooling is

$$h = \frac{\text{heat flux}}{T_s - T_w}$$

h is heat transfer coefficient $(W/m^2.s)$, $T_s$ is surface and $T_w$ water temperature. The heat transfer coefficient h depends on water flow rate. In secondary cooling solidification must be complete. Some of the issues are:

- Water spray must be distributed uniformly on the moving strand so that reheating of the strand does not occur. Non- uniform cooling leads to generation of thermal stresses on the surface and surface cracks may appear.
- Outer surface temperature should be greater than $850°C$ to avoid volumetric expansion accompanying due to transformation of austenite to ferrite.

Mist spray cooling i.e. mixture of air+ water provides more uniform cooling. Here high pressure air+ water mixture is sprayed on the metal surfaces. Some advantages are:

a) Uniform cooling
b) Less water requirement
c) Reduced surface cracking

**Products and casting defects**

Presently killed steels are cast continuously into slab for flat products and bloom and billet for structural products.

Defects in continuous casting originate from several factors like mould oscillation, mould flux, segregation coefficient of solute elements; phase transformation etc. In the following, a brief presentation is given on defect formation.

| Defects | | |
|---|---|---|
| Internal | Surface | shape |
| • Midway cracks<br>• Triple point cracks<br>• Center line cracks<br>• Diagonal cracks<br>• Center segregation and porosity<br>• Casting flux inclusion.<br>• Blow holes | • Longitudinal mid face and corner cracks<br>• Transverse mid face and corner cracks.<br>• Deep oscillation masks | Rhomboidity<br>Longitudinal depression ovality |

Cracks are originated in the cast product due to mechanical and thermal stresses. Material factors are also responsible

Mechanical stresses are created due to

i. Friction.
ii. Ferro static pressure.
iii. Bending and straightening operation.
iv. Roll pressure.

Mechanical stresses can be reduced by improving mold practices like

- Controlling powder feed rate
- Resonance in mold
- More accurate strand guidance
- Casting powder

Thermal stresses are due to non-uniform cooling in the secondary zone. Controlling water flux impinging the surface of the strand and minimizing reheating of strand can alleviate thermal stresses. Also air +water mist spray provides more uniform cooling.

Material factors are related to $\delta - \gamma$ transformation. High S and low $\mathrm{Mn}/s$ ratio cause mid face longitudinal cracks. Control of inclusion is also important.

Readers may go through the references given in this lecture.

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