Steel Making Fe-Met-II

Classification of Steels

Plain Carbon steels

i) Soft or low Carbon steels upto 0.15 % C

ii) Mild Steels in the range of 0.15 - 0.35 % C

iii) Medium Carbon Steels in the range of 0.35 - 0.63 % C

iv) High Carbon Steels — 0.63 - 1.75 % C

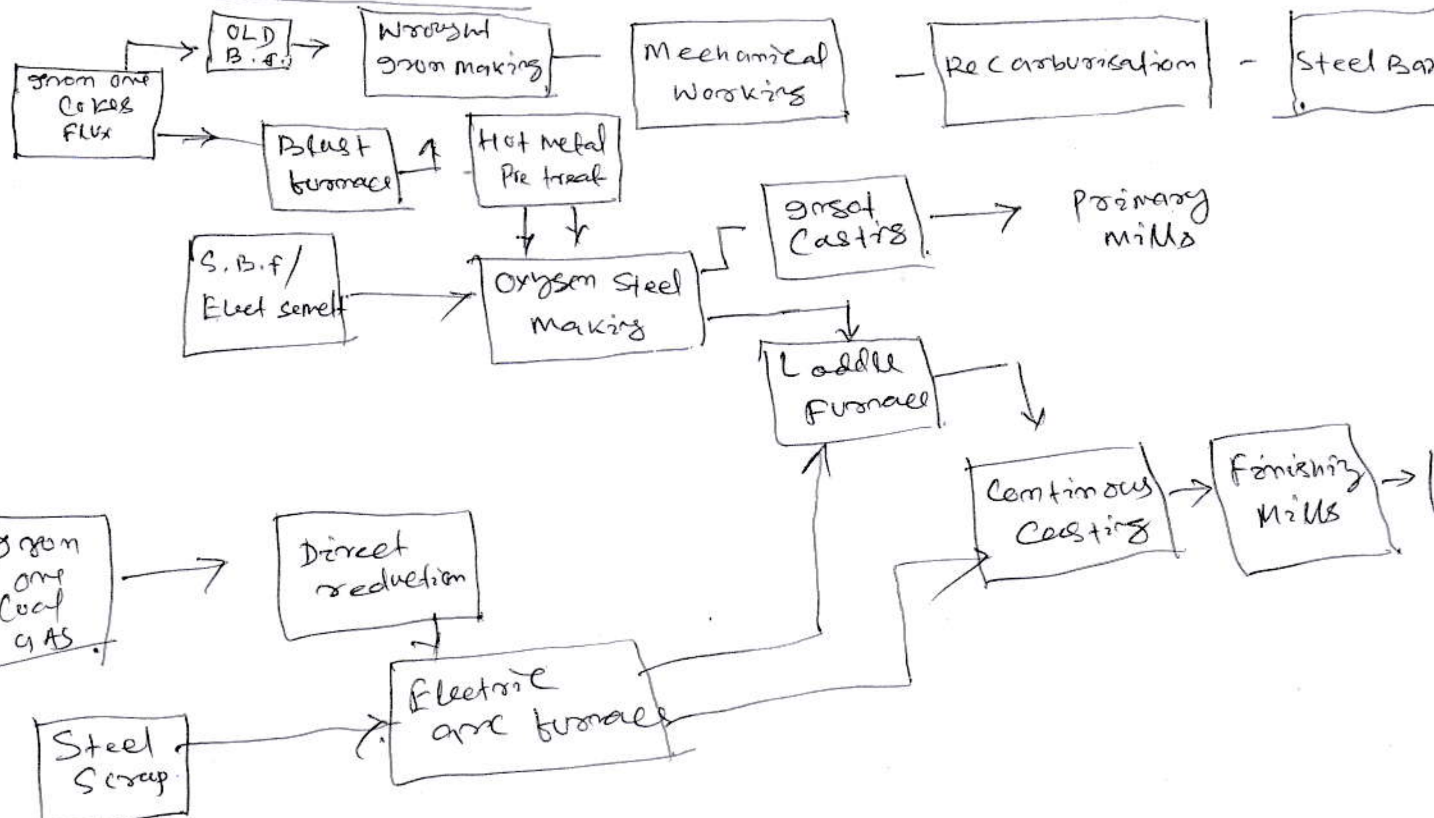
Alloy steels

i) low alloy Steels - upto 5 % total alloying Contents

ii) Medium alloy steels = 5 - 10 % total alloying

iii) High alloy steels - above 10 % total alloying,

Route of Steel making



Total process of steel making

a) Charge preparation, melting, refining, tapping, deoxidation, recarburisation, alloying, teeming, casting, stripping.

Acid Steel making and basic steel making process.

↓ Flux - SiO_2
lining - acid refractory

↓ Flux - lime
lining Basic refractory

Principle of Steel Making

Steel making is a refining or a oxidation process, the necessity to refine pig iron arises because it is quite impure. The oxygen steel making processes use pure oxygen modified conventional process use iron oxide, air and pure oxygen.

The basic reactions in steel making refining process

$\underline{Fe} + \underline{O} = (FeO)$

$\underline{C} + \underline{O} = \{CO\}$

$\underline{Si} + 2\underline{O} = (SiO_2)$

$\underline{Mn} + \underline{O} = (MnO)$

$2P + 5O = P_2O_5$

$\underline{S} + (CaO) = (CaS) + \underline{O}$

The product in the above reactions are stable at steel making temp. All reaction are in oxidation except sulphur which are treated separately.

(1) The oxidation of carbon the product, being a gas passes off into the atmosphere but the rest of oxide produced remain in contact with the iron melt in the form of a slag phase. The reaction should be forwarded in right preference to the oxidation of iron and that reversion of impurity to the metal phase

(2) From the law of mass action the required condition can be achived by increasing the activities of the reactants and decreasing those of product. activity of the impurity is fixed and hence can not be increased. the oxidising potential of an oxidising agent can be increased. $a_0 = 0.21$ and iron oxide $\rightarrow a_0 = 10^{-6} - 10^{-8}$ in slag phase and pure O_2 $a_0 = 1$ in place of air. once oxidising agent choosen it can not be increased.

(3) The activity of product can be decreased by combining it with oxide of opposite chemical character. acid oxide product is mixed with basic oxide ad vice-versa.

(4) The metal ad slag both, as thin liquids so that the metal being heavier settles down and slag floats on the top in the form of two immiscible liquids.

Mixer - (Inactive)

The hot metal from blast furnace needs to be stored in a vessel called mixer, because the blast furnace tap and steel making need not neccessarily be synchronised with respect to it's time and amount. The mixer acts as a buffer to store whatever metal comes from blast furnace and to supply the metal to SMS whenever required. It is a fire clay lined cylinderical vessel with a small fuel burner fitted-in to compensate for the head loss and to maintain the metal at the required temp. during it's storage

Acid burdening of B.F. and external desulphurisation

The blast furnace is operated for max. production rate at min. coke rate disregarding the composition of pig iron. The temp. of bf is low and rate of silica reduction is decreased. It leads to more viscous slag and as a result metal desulphurisation is very inefficient. The net result is that p.g. contain small amount of silicon but a high % of sulphur, so external desulphurisation is carried out and carried out by using good desulphurising agents like CaO, CaC_2, Na_2

Basic Burdening of Blast furnace and External Desiliconisation

When the the Al_2O_3 is high in the burden, the b.f. temp. has to be increased to keep slag free flowing since Al_2O_3 raised the softening point of slag. The basicity as well as the temp. are raised, to make the slags thin and basic to effectively desulphurised the metal inside the furnace to a level less than 0.06%.

Wrought iron making

Pure iron melts at 1536°C. The presence of impurities decrease the m.p. of iron so that pig iron is tapped from a b.f. around 1250°C - 1300°C in the form of a free flowing carbon-rich liquid. Before 1850s a max. attainable temp. in furnace fired with chemical fuels and cold air was the order of 1450°C. In such a furnace pig iron could be melted. As the impurities of iron are eliminated by oxidation, MP of iron increased and the refined mass becomes semi-solid. This pasty mass of iron, ~~increases and~~ pure but contaminated mech. by slag particles came to be known as wrought iron. It is malleable and soft. The process known as puddling process.

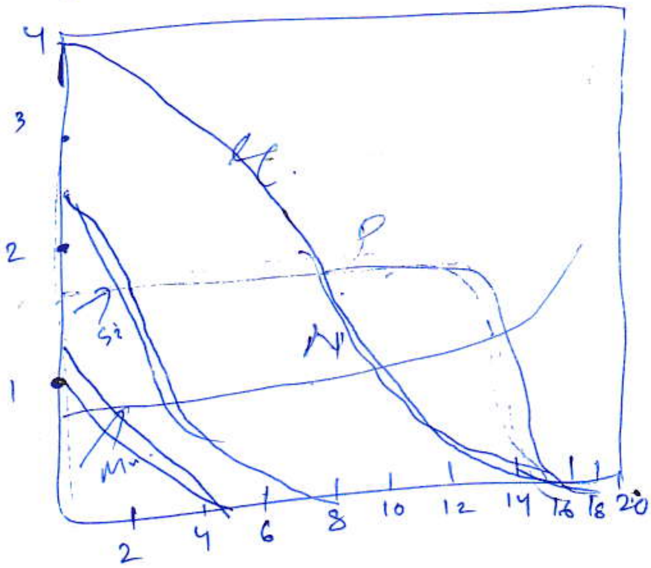
Cementation process. wrought iron was carburised for solid state by heating in contact with carbonaceous material for sufficiently long time for carbon to diffuse in. The iron carbon alled steel produced ad used for various application.

Crucible steel making

It is produced in crucible to produce molten steel. It was possible because as the carbon in steel increase m.p. the m.p. deacresed. then furnace could melt high carbon steel. This makes possibel to makes the steel in crucible.

Bessemer process

The molten iron was charged at arount 1300°c and blown for about 15 minutes when the final temp. was the order of 1600°C because of exothermic reaction of refining. The rate of refining was very fast because of turbulence created by blowing action. The process was autogenous.



Secondary Steel Making

The final refining and finishing is carried out in any one or more steel making processes.
The improvements aimed at were:

- improve deoxidation control
- remove inclusions by gentle bath stirring
- desulphurise steel by synthetic slag and injection metallurgy

Laddle furnace was used to achive

1) reheating of steel and control of teeming temp.
2) large alloying to produce high alloy steels
3) homogenization of heat w.r.t. to chemestry and temp.
4) produce ultra clean steel with an extended and gentle gas stirring.
5) deeper decarburisation.
6) desulphurisation for extra low end sulphur.
7) dephosphorisation for extra low P.
8) degassing
9) deoxidation.
10) improvement of alloying.

Process varieties

1. Stirring treatments
2. Synthetic slag refining with stirring
3. Vaccum treatment.
4. Decarburisation technique.
5. Tundish metallurgy.

Stirring techniques

Stirring a steel heat in the transfer ladle itself is the most simple kind of secondary treatment of steel. It was introduced to float deoxidation product, in the form of non-metallic inclusions and to obtain homogenous chemistry of the bath.
Stirring of the steel bath is achived by bubbling inert gas like nitrogen or argon in the steel bath held in the transfer laddle.

AOD

This is carried out in a special converter which is solid bottom vessel with tuyers provided on the sides. The tuyers are few in no. depending upon the capacity. The vessel is lined with basic magnesite refractory, molten charge from arc furnace is transfered to this vessel and blown with argon-oxygen mixture. The proportion of which varies from 1:3 in the begining through one stage and to 3:1 for final part of blow. temp. of bath 1710°c, coolants like nickel, stainless steel scrap, HC Fe.Cr, is added to arrive at correct down temp. The heat is finished by deoxidation of Fe-Si addition. The Cr, recovery is 97%. Some time Nitrogen substitute by argon.

Solidification of steel in ingot mould

Types of steel

1) Rimming steel – low deoxidation %C → < 0.15%.
2) semi killed steel – partial deoxidation %C 0.15 – 0.30%.
3) Killed steel – full deoxidation > 0.30% C.

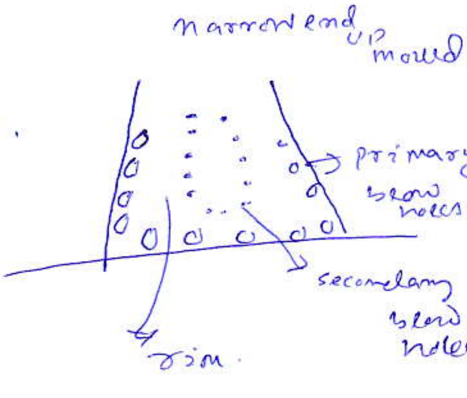
Rimming steel → Mn 0.2 – 0.3

high O_2 means low carbon
It produce a ductile steel due to low C

$[C] + [O] \rightarrow \{CO\}$, Fe-Mn or Al as deoxidiser.

boiling action a rimming action.
no deoxidation is carried out inside the steel making furnace.

Rim → 75 – 100 mm

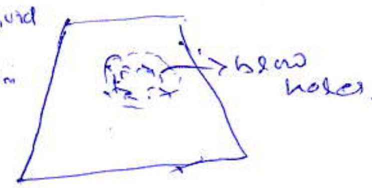


Semi killed steel

Product → plates, structural steels, partial deoxidised in laddle

Yield is higher, partial C → 0.15 – 0.30%.
Fe-Mn, ferrosilicon and aluminium may be used as deoxidisers.
The shrinkage of steel on solidification relieves the pressure developed in the liquid core of ingot due to gas evolution. The pipe is automatically compensated by the gas evolution and it's entrapment.
Chilled zone + columner zone

+ distrubed equiaxed zone



Killed steel

For forging and deep drawing. No gas evolution during solidification.
Yield is much less. All steels containing more than 0.3% C are killed. Fe-Si, silicon-manganese to the ladle & furnace.
wide end UP, Al is added. Yield is less.

Chilled zone + columner zone + equiaxed zone.

Ingot defect

Pipe

The volumetric contraction resulting on solidification appears in the form of a cavity known as a pipe, primary a open pipe get oxidised and does not weld during rolling. As a result that much of the ingot portion has to be discarded. It decreases the ingot yield. Being deep seated the secondary pipe does not get oxidised and welded up during rolling. Rimming and semi-killed steels show slight tendency for piping. Killed steel show max. amount pipe formation which decrease the ingot yield.

Blow holes — The entrapment of gas evolved during solidification of steel produces cavities known as blow holes in all except killed steel.
Blow holes are of two types

Primary blow holes > these are elongated or like honey comb and are located next to the ingot skin. The secondary blow holes are more spherical and are located further in. Formation of blow holes eliminate partially or fully the pipe and thereby increase the ingot yield during rolling provided these are located at proper depth from the surface of all sides of ingot.
Deep sealed blow holes do not open up and do not get oxidised during soaking. Such blow holes are welded up during rolling. Blow holes are closed to surface after get oxidised during soaking and get first punctured and then oxidised during rolling. Oxidised blow holes do not heal up during rolling and leave surface defects on the product.

Ingotism

After formation of initial chill layer further solidification results in the formation of dendrites which grow along their principal axis perpendicular mould walls their lateral growth is restricted due to adjoining dendrites giving rise to elongated crystals. Ingots possesing ingotism tend to crack during rolling unless in first pass of reduction kept low.

Segregation

It means departure from the average composition. If conc. is greater than average it is called the concentration, if it is less than average it is called -ve concentration. Steel is liquid solution of Si, C, P, Mn in iron and hence prone to segration during solidification.

Non - metallic inclusions

Indigenous - those arising in the course of steel making
Exogenous - those arising from mech. erosion of contacting refractory lining.

Indigenous inclusion comprise deoxidation product like oxides, sulphides, carbides, nitrides. Mn sulphide. Nitrides from only if residual Nitrogen level is high.
Proper care during refining and more particular during deoxidation can minimise inclusions.

Crack or Fissures due to uneven rapid heating and cooling of inner and outer surface of ingots. These can avoided by preventing for rapid cooling and reheating of an ingot.

Scab:- A projection on the side surface of an ingot caused by freezing of steel in a cavity in the mould wall or in a mould-

Lap:- Lappines or lap is a fold in ingot skin caused by freezing of a slowly rising top surface of the mould wall before pouring is over.

Splash — metal drops are thrown off due to impact of metal on mould bottom. If these drops stick to the mould wall they form seams in the rolled product. Flash → If steel entering the mould joining then solidified steel is called flash.

Lecture 32 Ingot Casting

Contents

Introduction
Ingot mould types
Mechanism of solidification
Ingot defects

Key words: Ingot casting, defects in casting, casting moulds

Introduction

Molten steel from BOF/EAF is tapped into a teeming ladle. Deoxidizers, decarburizes and alloying elements if required, are added for the final finishing with respect to oxygen content and other elements in steel. The steel may be degassed either before or during casting. In the modern steel plants, steel is cast continuously. In several small scale plants, particularly those based on induction melting furnaces ingot casting is practiced.

Ingot casting is done in cast iron moulds having square, round or polygon cross section. Ingots with square cross section are used for rolling into billets, rails and other structural sections. Whereas, ingots with rectangular cross section (also known as slab), are used for rolling into flat products. Round ingots are used for tube making. Polygon ingots are used to produce tyres, wheels, etc. Typically an ingot weighing 5-20 tons for rolling, whereas few hundred to 300 tons for forging.

Ingot mould types

Cast iron is used to fabricate the mould. Thermal coefficient of cast iron is lower than steel as a result, steel on solidification contracts more than cast iron which makes detachment of ingot easier from the mold. Inner walls of the mould are coated by tar or fine carbon. The coated material decomposes during solidification which prevents sticking of solidified ingots with the inner walls of the mold.

Molds are essentially of two types:

i) Wide end up or narrow end down as shown in figure 32.1 a)
ii) Narrow end up or big end down as shown in figure 32.1 (b)

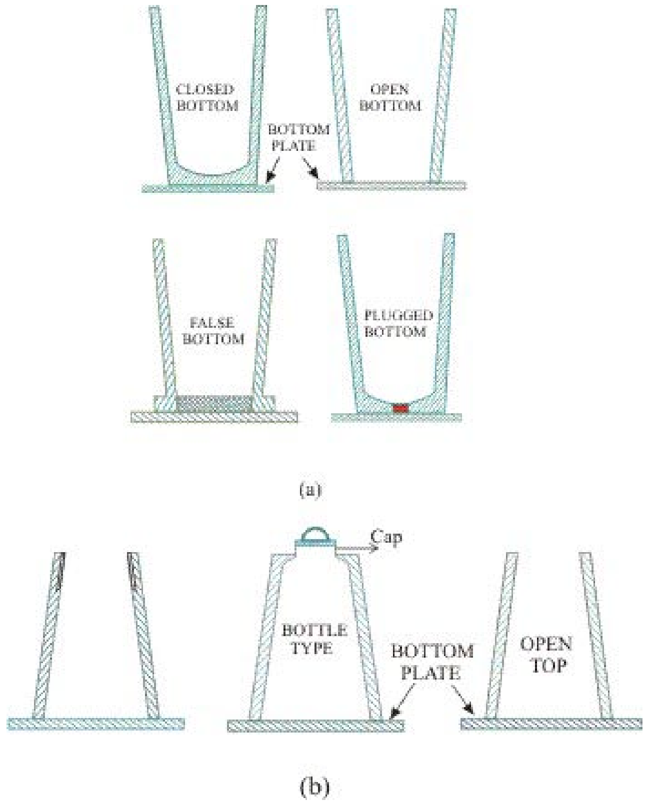


Figure 32.1(a) wide end up moulds (b) Narrow end up moulds

Wide end up moulds are used to produce forging ingots of killed plain carbon or alloy steels. Wide end up molds may have a solid bottom. Narrow end up molds are commonly used to produce rimming and semi-killed steel ingots. Narrow-end-up molds facilitates easy escape of rimming reaction product, CO.

Fully deoxidized or killed steel used for high quality forgings shrink on solidification and may lead to formation of pipe. Molds are generally provided with hot top which acts as reservoir to feed the metal and to avoid formation of pipe. Insulating and exothermic materials are put on the top ingot which ensures availability of hot metal towards the end of solidification.

Both bottom pouring and top pouring of steel are used in ingot casting.

Mechanism of solidification

Molds are water cooled. Killed steel solidifies in the ingot form as follows:

i) Metal near the mould walls and bottom is chilled by the cold surfaces and a thin shell or skin is formed on the ingot surface. This surface has a fine equiaxed grains and the skin. The formation of skin results in decrease in rate of solidification.
ii) Due to expansion of mould through the heat transferred from the solidifying steel and contraction of solidified skin an air gap forms between the mould and the skin.Th is results in decrease in the heat transfer rate, because air gap has a high thermal resistance to heat flow

iii) The solidification front perpendicular to the mold faces moves inwards and towards the centre as a result columnar grains form next to the chill surface. The columnar crystals rarely extend to the centre of the mould.

iv) The central portion of the ingot solidifies as equi-axed grains of bigger size due to slow rate of solidification.

The above zones of solidification depend on the evolution of CO gas due to carbon and oxygen reaction. In semi killed steels, not all oxygen removed from steel. Oxygen content of steel is very low. The necessary super saturation level of carbon and oxygen reaches towards the end of solidification. As a result the central zone of the equi- axed crystal is disturbed by way of formation of blow holes in the top middle potion of the ingot.

Solidification of rimming steels is controlled by evolution of CO during solidification. Rimming steels are not killed. The gas is evolved at the solid/liquid interface which stirs the molten steel during solidification. Stirring circulates molten steel which brings hot metal to the surface and solidification of steel at top is delayed. Columnar grain formation is prevented due to a more uniform temperature at interior of an ingot. This gives rise to rimming ingots in which gas is entrapped mechanically as blow holes.

Ingot defects: Causes and remedies

i) Pipe formation:

Cause: Steel contracts on solidification. The volumetric shrinkage leads to formation of pipe. In killed steels pipe formation occurs toward the end of solidification. Figure 32.2a shows primary and secondary pipe in narrow end up mould and 32.2 (b) in wide end up mould while casting killed steel. Only primary pipe can be seen in wide end up mould.

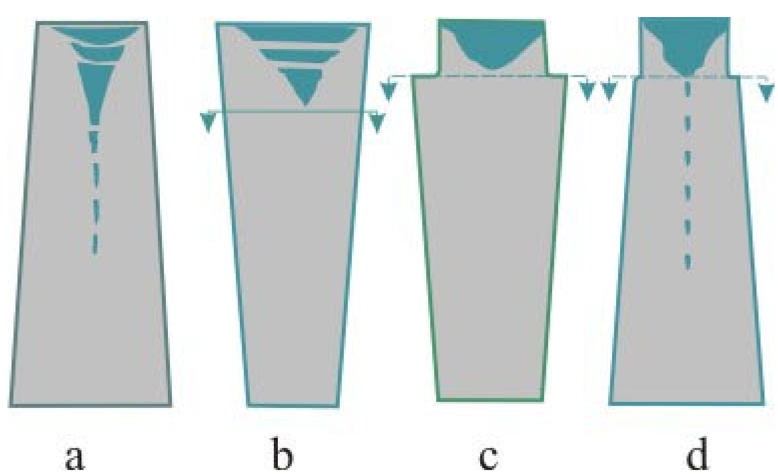


Figure 32.2 (a) Narrow end up mould showing long pipe in killed steel

Figure 32.2 (b) Wide end of mould showing pipe in killed steel

Rimming and semi-finished steel show very less tendency for pipe formation

Wide end up moulds show smaller pipe as compared with narrow end up mould (in figure 32.2 (a) longer pipe can be seen). The portion of ingot containing pipe has to be discarded which affects yields.

Remedy: use of hot top on the mold. The volume of the hot top is 10-15% higher than ingot volume. Pipe formation is restricted in the hot top which can be discarded. Use of exothermic materials in the hot top keeps the metal hot in the top portion and pipe formation can be avoided. Another method is to pour extra mass of metal.

ii) Blow holes

Cause: Evolution of gas during solidification of steel. Entrapment of gas produces blow holes in the ingot. Blow holes located inside the ingot can be welded during rolling. Rimming steels show blow holes due to rimming reaction between carbon and oxygen. The rimming reaction produces CO, which when is unable to escape during solidification, produces blow holes. Semi-killed steels also show tendency to blow hole formation.

Remedy: Control of gas evolution during solidification so that blow hole forms only within the ingot skin of adequate thickness.

Segregation: It is the difference in composition of steel within the ingot than some average composition. Segregation is due to

a) Difference in solubility of solute elements in liquid and solid steel i.e. partition coefficient of element in steel. Partition coefficient of solute (K) is defined as

$$K = \frac{Concentration\ of\ solute\ in\ solid}{Concentration\ os\ the\ solute\ in\ liquid}$$

The value of K ≤ 1. The solute elements whose K = 1 do not segregate. All elements whose $K < 1$ tend to segregate.

b) Rate of solidification: faster rate of solidification avoids the elements to segregate. The initial chill layer of ingot has practically the same composition as that of liquid steel. Decrease in rate of solidification causes elements to segregate.
c) Larger size ingots are prone to segregation than smaller size ones. Larger size ingots require more time for solidification.

Remedy: soaking of ingots at high temperature can minimize segregation.

Non metallic inclusions:

Non metallic inclusions are inorganic oxides, sulphides and nitrides formed by reaction between metal like $\mathrm{Fe}, \mathrm{Ti}, \mathrm{Zr}, \mathrm{Mn}, \mathrm{Si}, \mathrm{Al}$ with non metallic elements like oxygen, nitrogen, sulphur etc.. An inclusion is a mismatch with the steel matrix. ***See lectures 27-30 for details about inclusions.***

Fine size inclusions when distributed uniformly are not harmful. Non deformable inclusions like Al_2O_3 are undesirable.

Inclusion modification is the remedy to alleviate the harmful effect of inclusions on properties of steel.

Ingot cracks

Surface cracks are formed due to friction between mold and ingot surface. The improper design of mold taper and corner radius cause surface cracks. Different types of cracks are:

Transverse cracks: They are parallel to the base of ingot and are formed due to longitudinal tension in the ingot skin. As the aspect ratio of the ingot increases, tendency to transverse crack formation increases.

Longitudinal cracks are formed due to lateral tension in the skin. They are parallel to vertical axis of ingot. Alloy steels are more prone to longitudinal cracks than mild steels.

Sub- cutaneous cracks are internal fissures close to the surface. The cracks are formed due to thermal shocks.

Restriction cracks can be near the corner radius of the ingot.

Smooth corners of the mould and gradual curvature minimize restriction cracks.

References:

RH Tupkary, VR Tupkary: An introduction to modern steel making.

Lecture 33 continuous casting of steel

*Content*s

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.

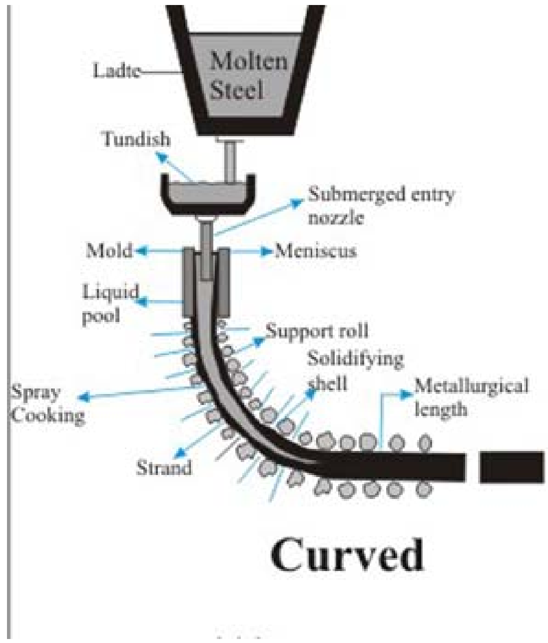


Figure 33.1 Arrangement of tundish, mold and water spray in a curved mold machine (paste figure 2.3a)

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.

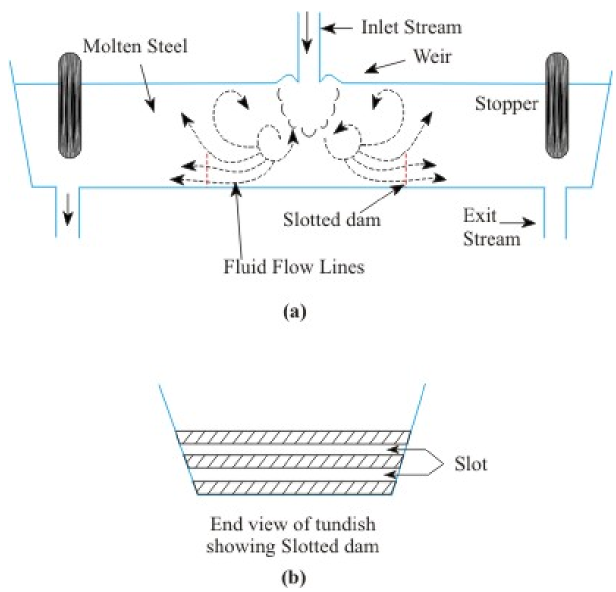


Figure 33.2: Tundish with flow control device, namely weir and slotted dam

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.

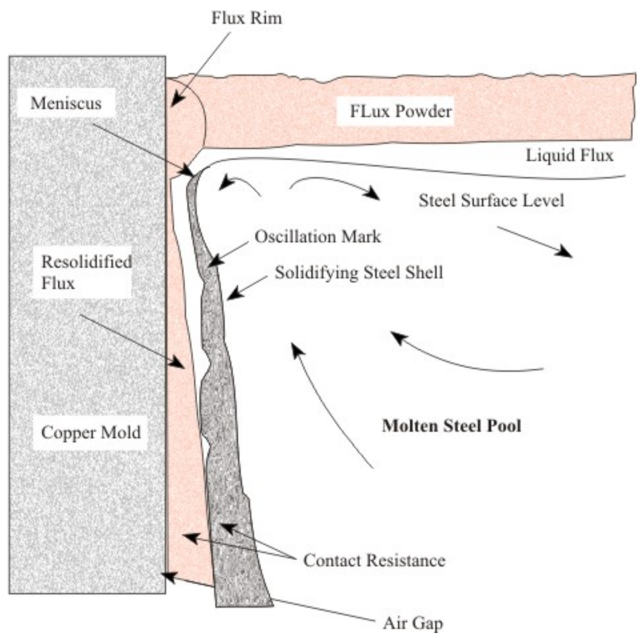


Figure 33.2: Role of flux in continuous casting mold

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 kg/sm, U_s casting speed m/s, δ is boundary layer thickness, ρ is density of flux, μ is viscosity of slag (kg/ms).

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

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

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

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 $(0.08\%$ 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.

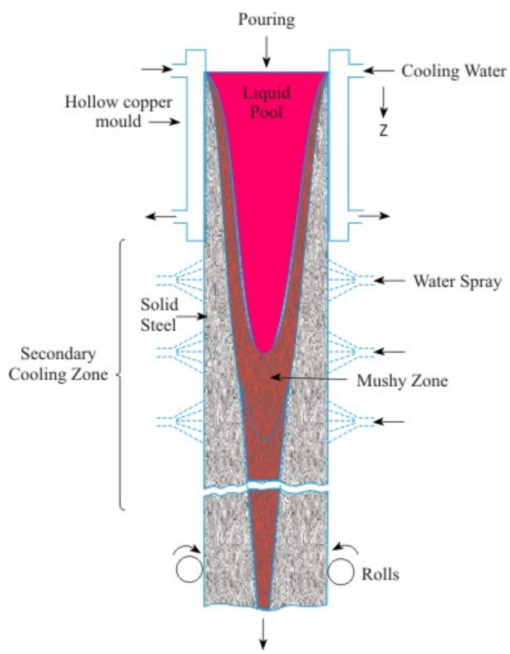


Figure 33.3: Heat transfer in the mold and secondary cooling zone and the formation of solid shell. Mushy zone and liquid core can also be seen

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 • Triple point cracks • Center line cracks • Diagonal cracks • Center segregation and porosity • Casting flux inclusion. • Blow holes	• Longitudinal mid face and corner cracks • Transverse mid face and corner cracks. • Deep oscillation masks	Rhomboidity 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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