UNIT 4

Clean Steel

- Clean steel refers to steel which is free from inclusions. Inclusions are non metallic particles embedded in the steel matrix.
- Practically it is not possible to produce steel without any inclusion.
- Therefore we can talk about cleaner steel.
- Which steel is clean would depend on the applications.
- In this connection it is important to know that there is a limiting size below which inclusion does not affect mechanical property.

Table lists some applications which can tolerate some minimum inclusions size:

Steel product	Allowed impurity in ppm	Allowed size(μm)
Automotive and deep drawing sheet	C<30, N<30	100
Line pipes	S<30, N<50, TO<30	100
Bearings	TO<10	15
Tire cord	H<2N<40, TO<15	10
Heavy plate steels	H<2 N+30 to 40, TO<20	13
Wires	N<40, TO<15	20
Drawn and ironed cans	C<30, N<40, TO<20	20

TYPES OF INCLUSIONS:

- Inclusions are chemical compounds of metals like (Fe, Mn, Al, Si, Ca etc) with non metals (O, S, N, C, H).
- Different types are:
  - Oxides:FeO,Al_2O_3,SiO_2,MnO,Al_2O_3.SiO_2,FeO.Al_2O_3,MgO.Al_2O_3,MnO.SiO_2
  - Sulphides: FeS,CaS,MnS,MgS,Ce_2S_3 ,
  - Nitirides: TiN,AlN,VN,BN etc.
  - Oxysulphides: MnS.MnO,Al_2O_3.CaS, etc
  - Carbonitrides: Titanium/ vanadium/Niobium carbonitirides, etc
  - Phosphides: Fe_3P,Fe_2P,Mn_5P_2

BY MINERALOGICAL CONTENT, OXYGEN INCLUSIONS ARE CLASSIFIED:

- Free oxides - FeO,MnO,Cr_2O_3,SiO_2(quartz)Al_2O_3 (corundum) and other;
- Spinels – Ferrites, chromites and aluminates.
- Silicates- SiO2 with a mixture of iron, manganese, chromium, aluminum and tungsten oxides and also crystalline silicates
- By stability, non –metallic inclusions are rather stable or unstable. Unstable inclusions are iron and manganese sulfides and also some free oxides.

Morphology

- Globular shape is desirable. Certain inclusions like MnS, oxysulphides, iron aluminates and silicates are globular.
- Platelet shape: undesirable. Al deoxidized steels contain MnS in the form of thin films located along the grain boundaries.
- Polyhedral inclusions are not very harmful.

Size of inclusions

- There are micro inclusions(size 1−100μm) and macro-inclusions (size greater than100μm) . Macro inclusions are harmful.
- Micro inclusions are beneficial as they restrict grain growth, increase yield strength and hardness.
- Micro- inclusions act as nuclei for precipitation of carbides and nitrides.
- Macro- inclusions must be removed. Micro inclusions can be used to enhance strengthening by dispersing them uniformly in the matrix.

PROPERTIES OF INCLUSIONS:

- *i) Thermal expansion.*
- An inclusion is a mismatch with the steel matrix. There are inclusions like MnS,CaS, etc. which have thermal expansion greater than steel matrix. On heating steel with these types of inclusions voids or parting of the matrix can occur. The void can act as cracks.
- On the other hand Al_2O_3,SiO_2 and $CaO.Al_2O_3$, etc inclusions have thermal expansion smaller than steel matrix. On heating steels with these type of inclusions internal stresses of thermal origin can develop.

DENSITY AND MELTING POINT

ii) Density and melting point

Composition of inclusions	Melting point(^0C)	Density at $20^0C(g/cm^3)$
Ferrous oxides (FeO)	1369	5.8
Manganous oxides (MnO)	1785	5.5
Silica	1710	2.2-2.6
Alumina ($Al_2 O_3$)	2050	4.0
Chrome oxide Cr2	2280	5.0
Titanium oxide, TiO_2	1825	4.2
Zirconium oxide, ZrO_2	2700	5.75
Iron silicate, $(FeO)_2SiO_2$	1205	4.35
Iron sulphide, FeS	988	4.6
Manganese sulphide, MnS	1620	4.04
Magnesia, MgO	2800	3.58

PLASTIC DEFORMABILITY

- The plastic deformability of an inclusion will govern any change in its shape under the action of external forces and will determine the amplitude of stress concentration.
- Brittle inclusions are dangerous as they may crack and cause fracture of the component under the application of external force.
- The majority of inclusions belong to pseudo-ternary system: $CaO-SiO_2-Al_2O_3$, $MgO-SiO_2-Al_2O_3$, $CaO-SiO_2-Cr_2O_3$ etc.
- Sulphide inclusions are mainly MnS. Other elements like Ti, Zr, rare earths, Nb, V etc. usually appear as solid solutions in existing inclusion phases.

According to Kieslling

- (i) Calcium aluminates and Al2O3 inclusions in steel are undeformable at temperatures of interest in steelmaking.
- (ii) Spinel type double oxides AOB2O3 (where A is Ca, Fe(l), Mg and Mn,and B is Al,(Cr etc) are deformable at temperatures greater than1200℃ .
- (iii) Silicates are deformable at higher temperature range. The extent of deformation depends on their chemical compositions. Silicates are not deformable at room temperature.

- (iv) FeO,MnO and (Fe,Mn)O are plastic at room temperature but gradually lose plasticity above 400℃.
- (v) MnS which is highly deformable at 1000℃ temperature but becomes slightly less deformable above 1000℃ .
- (vi) Pure silica is not deformable up to 1300℃

INCLUSION ASSESSMENT

- Inclusion counts are performed to assess their shape, quantity and distribution to assess about the cleanliness of steel.
- The routine plant procedure employes the microscopic method. From the shape of the inclusion and knowledge of the steelmaking process in a plant, it is inferred to whether it is silica/ silicate, aluminate or sulphide inclusion
- Electron probe micro analyzer enables to determine the chemical composition of individual inclusions.

- The energy dispersive x-ray analysis (EDX) attachment for SEM allows quantitative chemical analysis of inclusion as well as quantitative mapping of distribution of various elements in and around the inclusions.
- Quantimet has an optical microscope fitted with video screen and associated microprocessor-based instrumentation. It can scan the specimen very quickly and provide a variety of information such as inclusion size, distribution, number, volume fraction, etc.

- Total oxide inclusion content of steel can be determined from the analysis of oxygen by sampling and the use of vacuum /inert gas fusion apparatus.
- Radioactive tracers can identify the origin of inclusion distributions, etc.

WHY INCLUSION CONTROL IS NECESSARY

- Impact properties are adversely affected with an increase in volume fraction of inclusion as well as inclusion length; spherical inclusions are better. Brittle inclusions or inclusions that have low bond strength with the matrix break up during early straining and create voids at the inclusion/ matrix interface.
- Hot fatigue strength of high strength steel is reduced by surface and subsurface inclusions those have lower expansion coefficient than steel

- The hot workability of steel is affected by the low deformability of inclusions
- Anisotropy of a property is caused by orientation of elongated inclusions along the direction of working. Macro inclusions of sulphides are desirable for better steel machining properties.

Sources of inclusion formation

- Inclusions can form either **(a) during transfer of molten steel from one reactor to other or (b) during solidification of steel or during solid state processing by any of the following mechanisms**

i. Reaction between rejected solute elements during solidification, for example, reaction between sulphur and manganese, and between oxygen and aluminium etc.

ii. Mechanical and chemical erosion of refractory and other materials.

iii. Oxygen pickup by teeming stream and consequent oxide formation.

iv. Chemical reactions.

- Inclusions produced by mechanism **(i) are called endogenous, whereas mechanisms ii and iii produce exogenous inclusions. Inclusions can form during**
- a) Tapping of molten stream from BOF/EAF to ladle. Erosion of launder refractory is the possible source. Pick up of oxygen from atmosphere and formation of FeO.
- b) Treatment of steel in ladle. Here molten steel is in contact with the refractory. Also during deoxidation and synthetic slag treatment oxide/sulphide inclusions may form

- c) Teeming of molten stream. Molten steel is in contact with stopper and nozzle refractory and elements like Ti, Mg etc., which can form oxides. Air entrainment into molten steel stream brings oxygen and FeO formation is initiated.
- d) Solidification in mould due to precipitation of excess solute elements.
- e) Final finishing operations like heat treatment and deformation processing. Here steel is heated to high temperature which may cause surface oxidation, surface sulphurization, inner oxidation,etc.
- f) Fusion welding. Oxidation of weld pool, electrode coatings are the possible source of inclusions in fusion welding processes.

Control of inclusions

- Inclusions can be controlled either at
  - **(a) during liquid steel processing stage or**
  - **(b) during solid state processing.**

- *Liquid state processing*
- During tapping of molten stream from BOF/EAF carry- over of slag must be minimized if not prevented. BOF slags are highly oxidizing in nature and contain oxides like FeO,MnO,SiO2, CaO, MgO etc. These oxides react with Al during ladle treatment and lead to inclusion formation.

- ii. Molten steel stream after treatment in the ladle is teemed into tundish and then from tundish to mould in the continuous casting.

- iii. Selection of tundish flux
  - Tundish flux should be selected such that it can easily absorb inclusions floating in the tundish .At the same time flux should also cover molten steel to prevent oxidation.

- iv. Tundish operation
  - Now a days sequence casting is commonly adopted in continuous casting. During ladle change- over tundish feeds the molten steel to different molds of the continuous casting machine. In this situation care must be exercised to ovoid slag entrainment into mold due to vortex formation. Tundish should not be emptied completely. Also tundish lining material should be inert with Al

- v. Inclusion can also form in the mold during solidification. As the steel solidifies the excess solute elements like oxygen, sulphur, manganese etc are rejected and lead to inclusions formation.

- Segregation during solidification must be avoided. Here stirring of molten steel is effective to minimize the segregation and inclusion formation
- *Solid state processing*
  - In the solid state processing steel is heated to a temperature ranging in between 800−1200°C to perform heat treatment and hot working. Here steel must be heated under inert atmosphere to avoid oxidation. During fusion welding, liquid pool is in contact with air and steel is prone to oxidation. Inert shielding may avoid the inclusion formation.

Ingot Casting

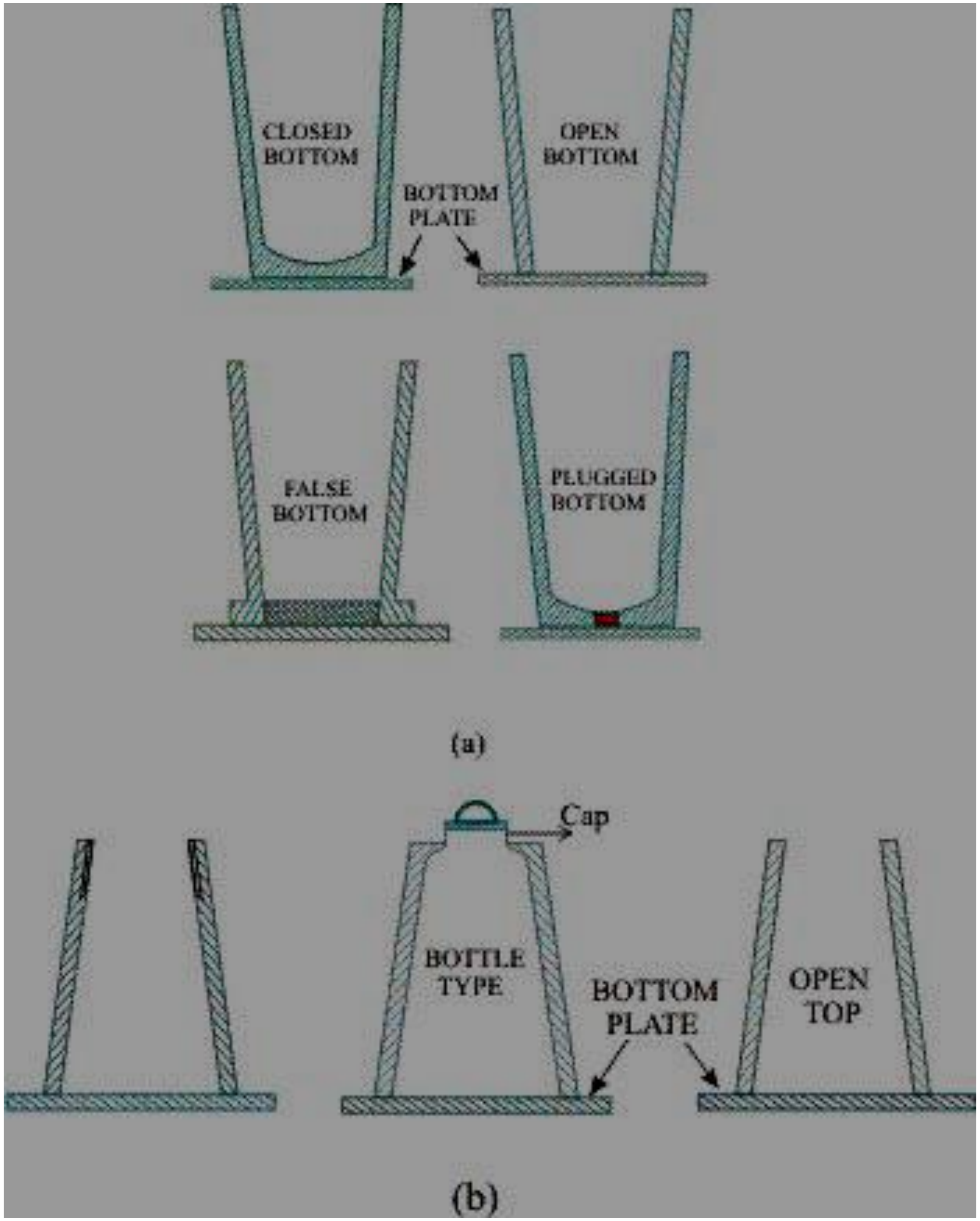
- **Introduction**
- Molten steel from BOF/EAF is tapped into a teeming ladle. Deoxidizers, decarburizes and alloying elements if required, are added for the final finishing with respect to oxygen content and other elements in steel.
- The steel may be degassed either before or during casting. In the 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 (a)
- ii) Narrow end up or big end down as shown in figure (b)



CLOSED
BOTTOM
OPEN
BOTTOM
BOTTOM
PLATE
FALSE
BOTTOM
PLUGGED
BOTTOM
(a)
Cap
BOTTLE
TYPE
BOTTOM
PLATE
OPEN
TOP
(b)

- 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.

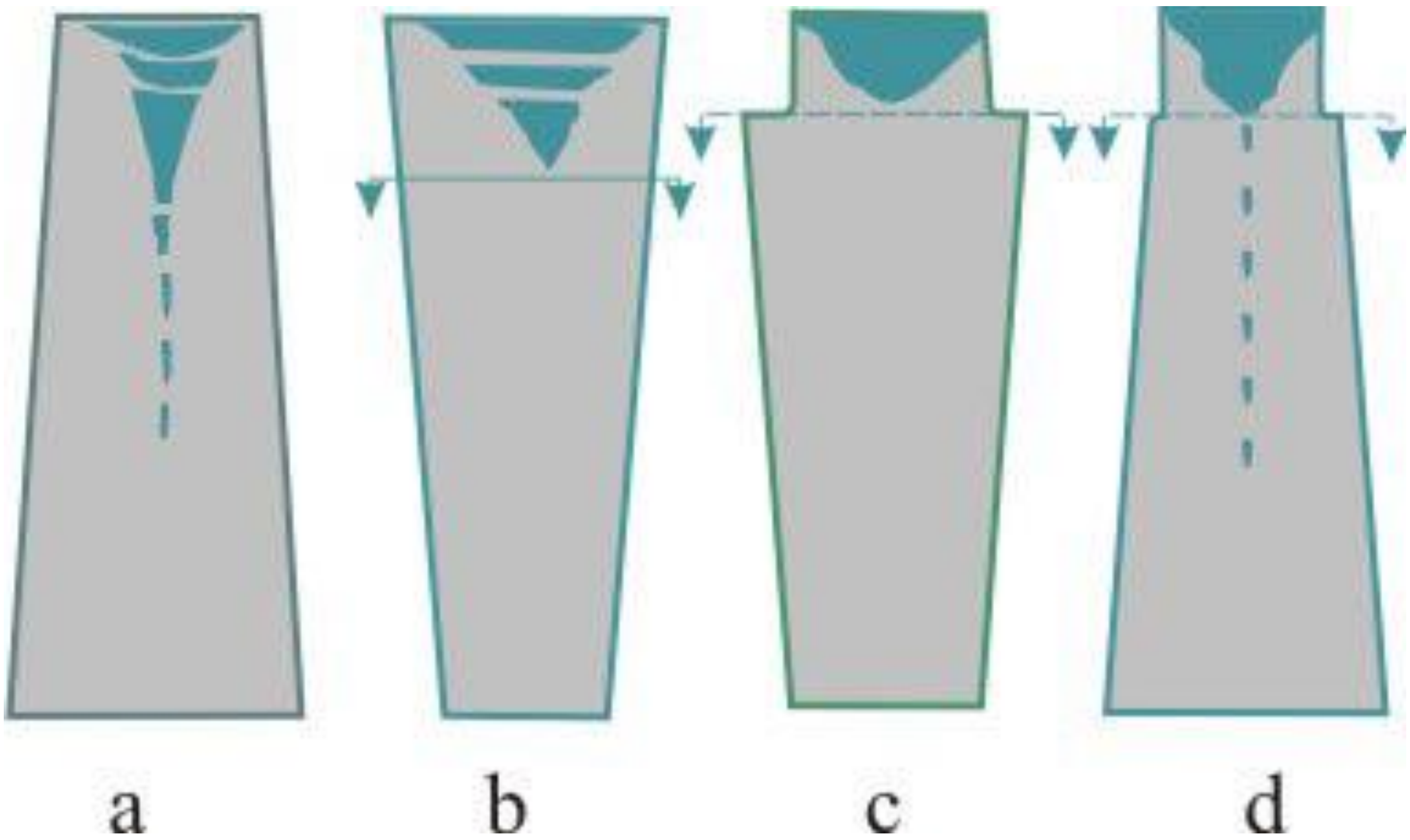
- The above zones of solidification depend on the evolution of CO gas due to carbon and oxygen reaction. In semi killed steels, not all oxygen removed from steel.
- Oxygen content of steel is very low. The necessary super saturation level of carbon and oxygen reaches towards the end of solidification.
- 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 a shows primary and secondary pipe in narrow end up mould and (b) in wide end up mould while casting killed steel. Only primary pipe can be seen in wide end up mould.*


a
b
c
d

- 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 (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 $K \leq 1$. The solute elements whose $K = 1$ do not segregate. All elements whose < 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 Fe,Ti,Zr,Mn,Si,Al with non metallic elements like oxygen, nitrogen, sulphur etc.. An inclusion is a mismatch with the steel matrix.
- 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

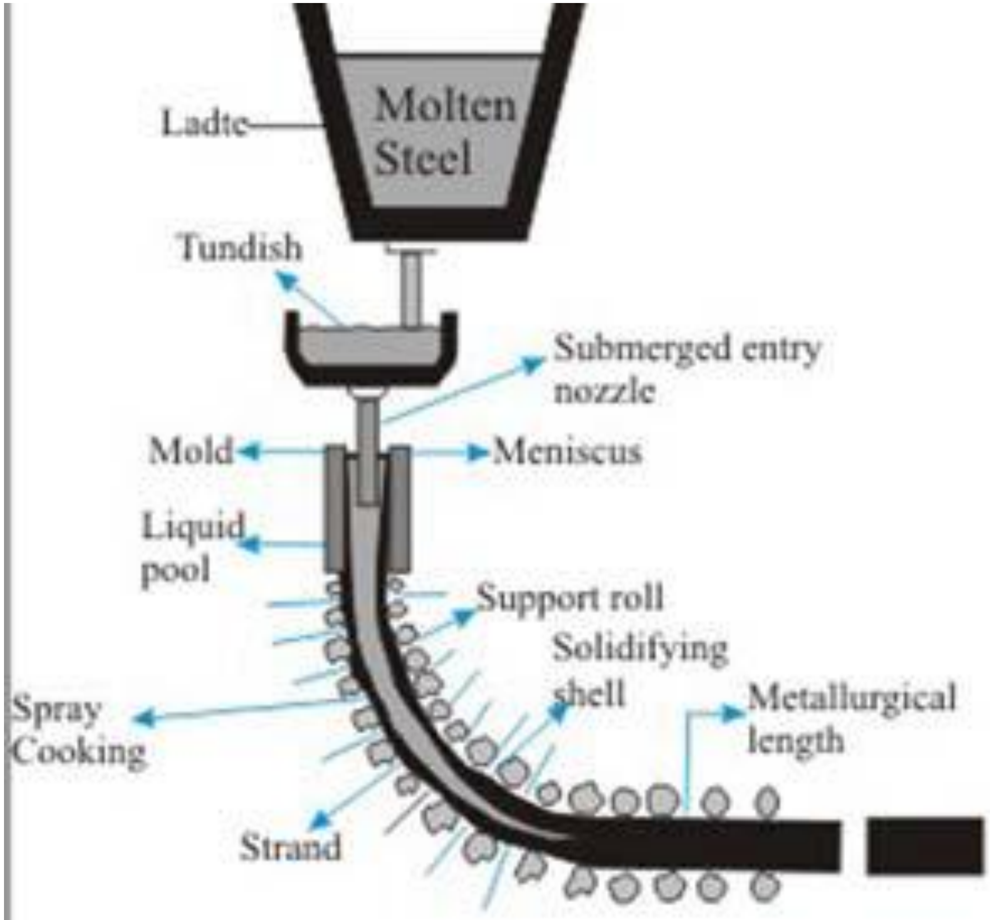
CONTINUOUS CASTING OF STEEL

- **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, the arrangement of tundish, mold and water spray is shown.


Ladte
Molten Steel
Tundish
Submerged entry nozzle
Mold
Meniscus
Liquid pool
Support roll
Solidifying shell
Metallurgical length
Spray Cooking
Strand

Curved

- *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.

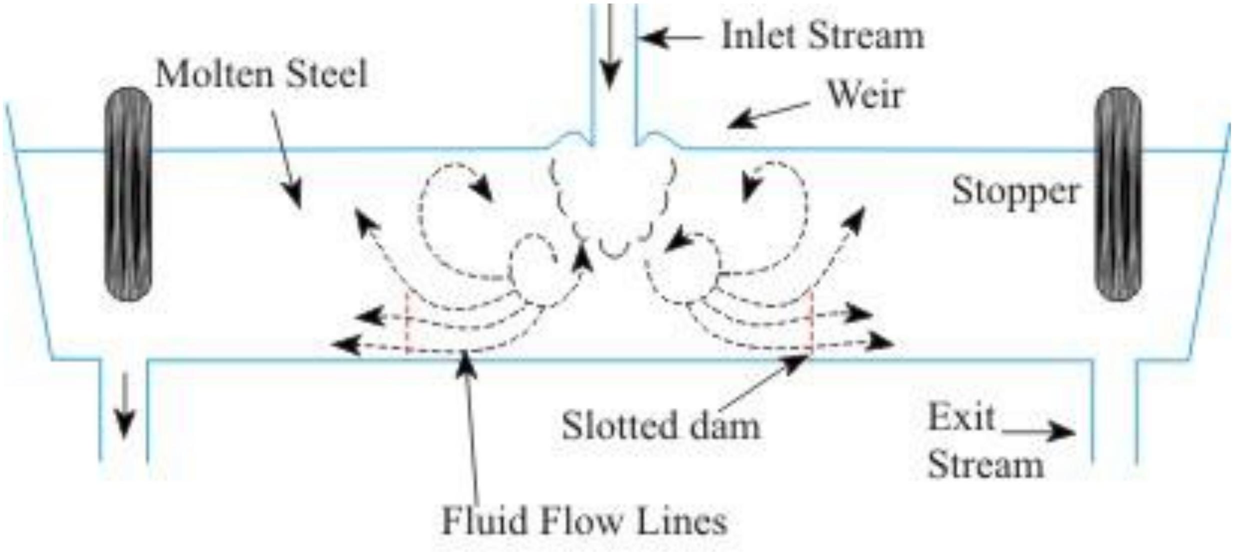
- Location of ladles stream in the tundish is important.
- It may be located symmetric or asymmetric to the centre of the tundish depending on the number of mold.
- For single strand machines, molten stream enters from one side and exits the other side of the tundish.
- In multi-strand tundishes, ladle stream is either at the centre of the tundish or displaced to the width side of the tundish.

INCLUSION REMOVAL

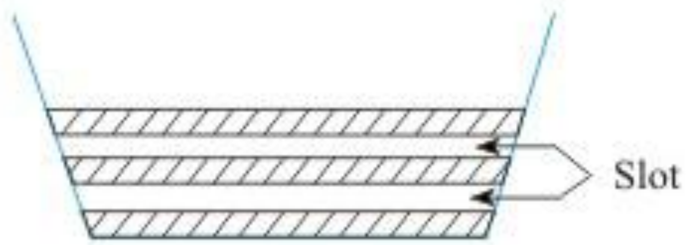
- Tundish helps to remove inclusions during the process of continuous casting.
- For this purpose liquid steel flow in the tundish is modified by inserting dams, weirs, slotted dams etc.
- The whole idea is to utilize the residence time available before steel leaves the tundish.

- 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.



(a)



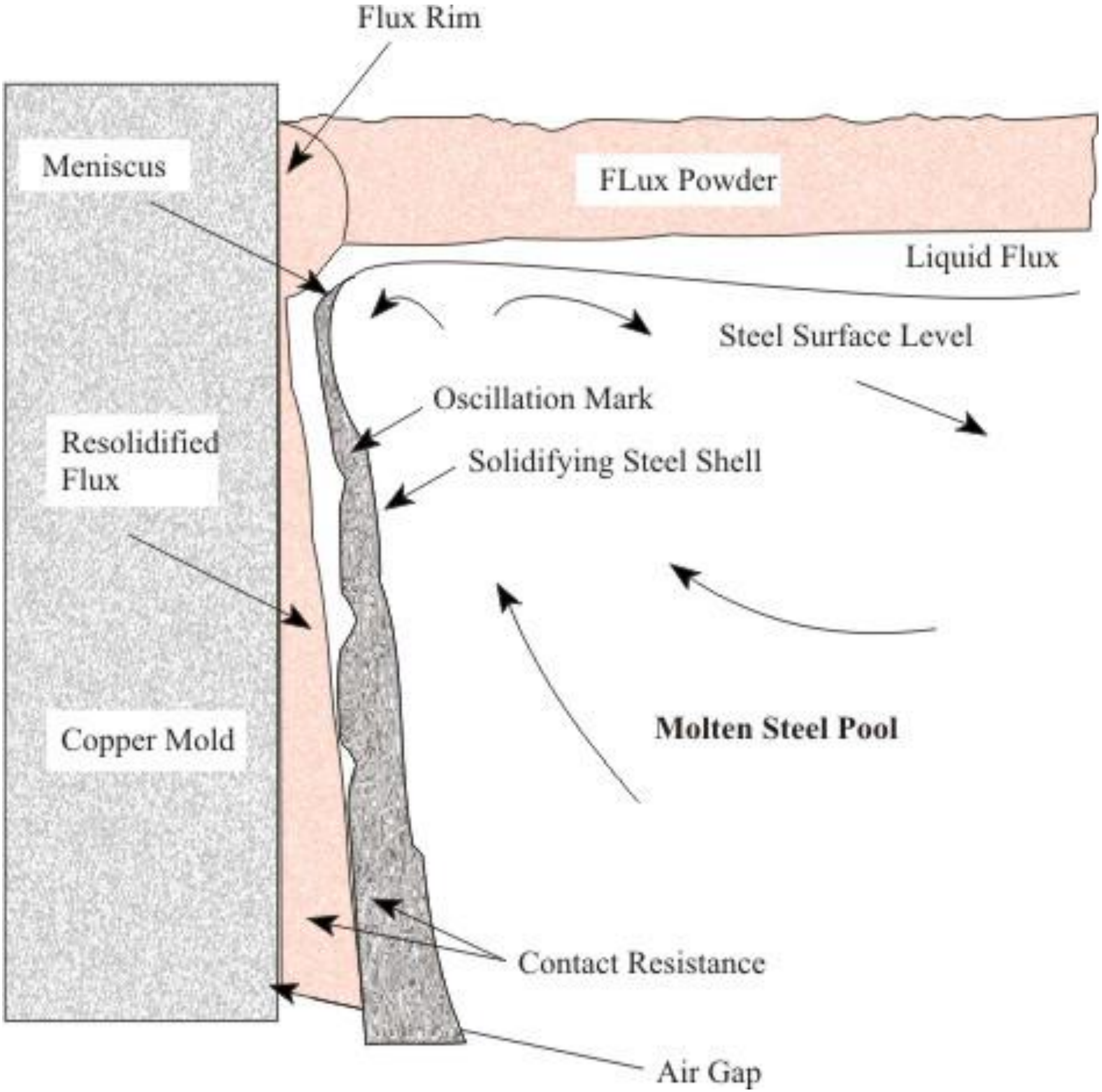
End view of tundish
showing Slotted dam

(b)

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

- 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.


Flux Rim
Meniscus
FLux Powder
Liquid Flux
Steel Surface Level
Oscillation Mark
Solidifying Steel Shell
Resolidified
Flux
Molten Steel Pool
Copper Mold
Contact Resistance
Air Gap

- 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 100mm X 100 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 0.75-1.4m 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.

Secondary cooling

- Below the mold partially solidification strand is water sprayed to complete the solidification. Parameters affecting the heat extraction are:
  - Water drop flux
  - Mean drop size
  - Droplet velocity hitting the strands
  - 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 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 the nozzle is important.

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
  - Friction
  - Ferro static Pressure
  - Bending and Straightening operation
  - 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