

## Lecture 32 Ingot Casting

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**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.

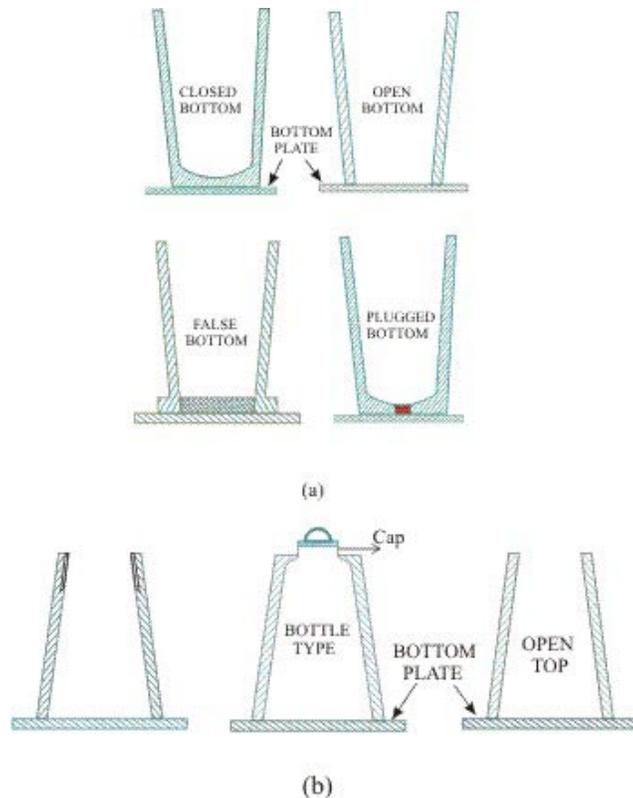
Ingot casting is done in cast iron moulds having square, round or polygon cross section. Ingots with square cross section are used for rolling into billets, rails and other structural sections. Whereas, ingots with rectangular cross section (also known as slab), are used for rolling into flat products. 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 moulds may have a solid bottom. Narrow end up moulds are commonly used to produce rimming and semi-killed steel ingots. Narrow-end-up moulds 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. This 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.

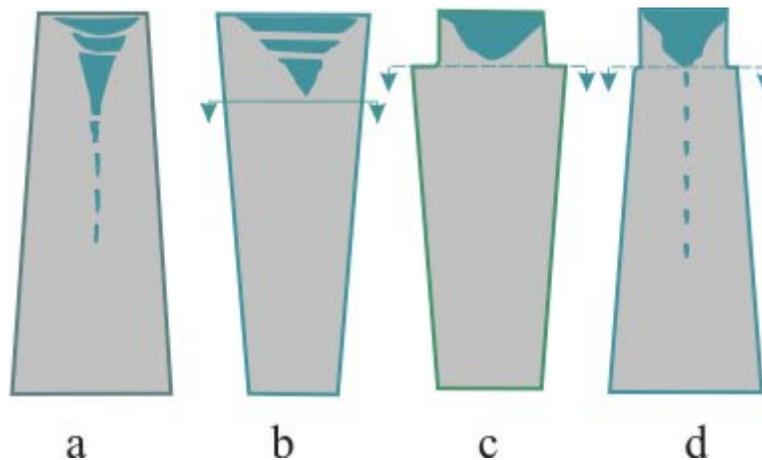
The above zones of solidification depend on the evolution of CO gas due to carbon and oxygen reaction. In semi killed steels, not all oxygen removed from steel. Oxygen content of steel is very low. The necessary super saturation level of carbon and oxygen reaches towards the end of solidification. As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

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

The value of  $K \leq 1$ . 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 Fe, Ti, Zr, Mn, Si, 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.