Iron Making and Steel Making
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Module – 10
Lecture – 48
Morphology of solidification Structure and Ingot casting

In the last two lectures we have discussed the two fundamental aspects of casting like heat transfer and segregation. And, in this lecture I will cover morphology of solidification structure and subsequently the ingot Casting.

I will briefly discuss the ingot casting because ingot casting nowadays it is not used too much and only some ingots are cast for forging purpose. Usually, for flat products ingots are not cast today; flat products are primarily made by the continuous casting.

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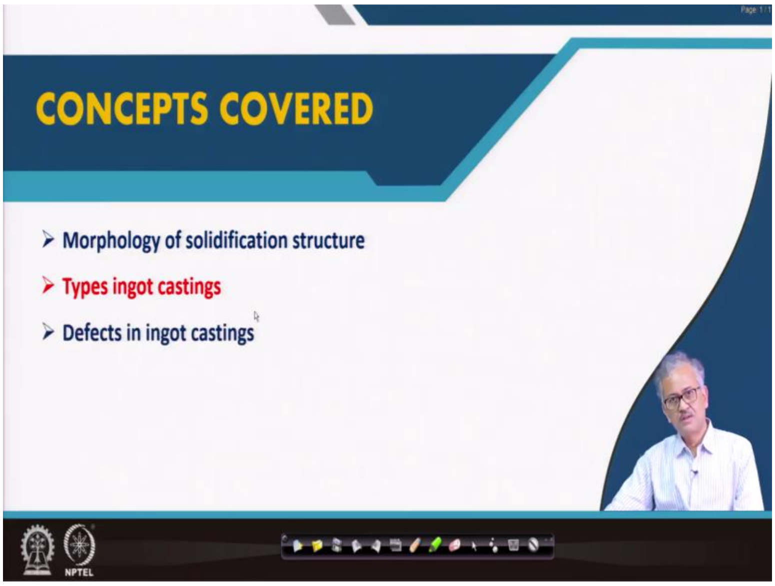

So, the topics covered will include the morphology of solidification structure, how it evolves during solidification, types of ingot casting and associated defects.

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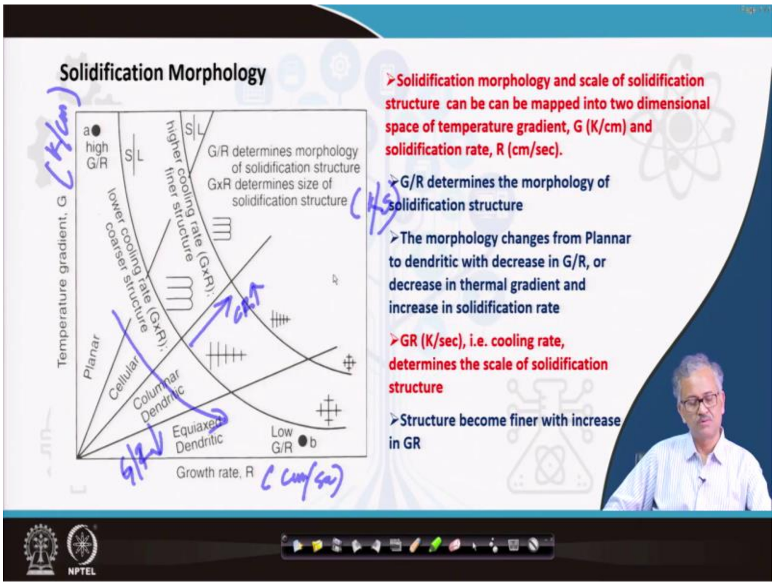

First we will discuss the evolution of solidification morphology during the course of solidification. In a two dimensional domain of thermal gradient (G) and solidification rate (R), all possible solidification morphologies like planar, columnar, dendritic (unidirectional dendrites with branches) and equiaxed dendritic (random dendritic growth), could be mapped, as shown in the figure 48.1. Scale of solidification structure (fine/coarse) can also be mapped in the G, R map. G/R provides the solidification morphology and GR gives the scale of solidification structure. High G/R yields columnar structure, which subsequently converts to dendritic and equi-axed dendritic with decrease in G/R value. GR is basically the cooling rate and high GR or high cooling rate yields finer structure due to restricted growth. Besides this, large undercooling due to high heat extraction rate or, constitutional super-cooling also leads to equi-axed dendritic structure through large and random nucleation.

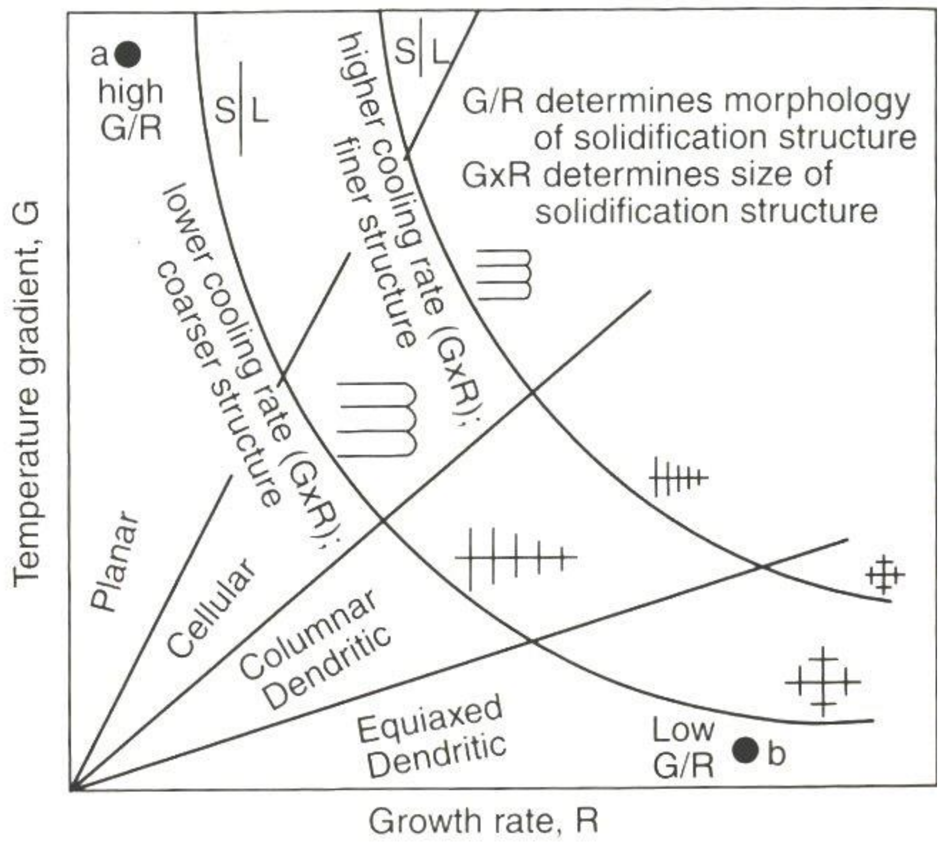

Figure 48.1: Mapping of solidification morphology and scale of solidification structure against two dimensional domain of temperature gradient (G) and solidification rate ®

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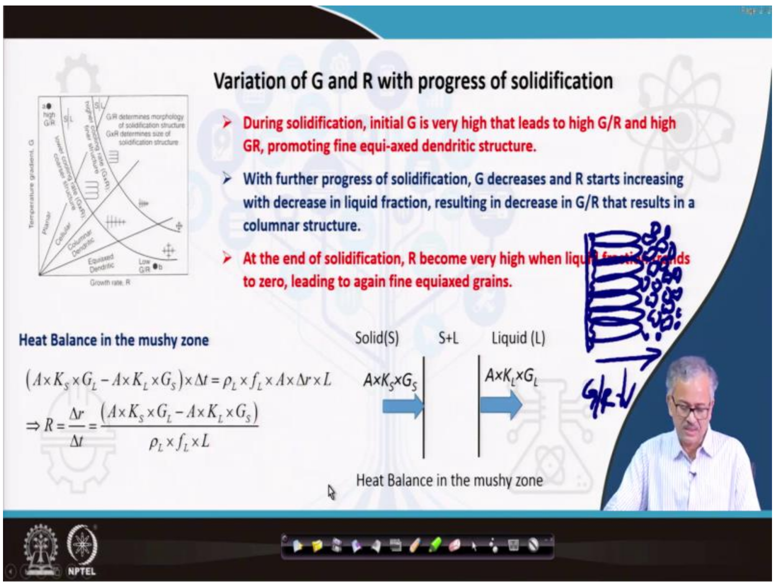

Now, consider the evolution of solidification morphology in a cast structure. When liquid metal solidify in the mold, fist a solidified skin forms on the mould surface which has an fine equi-axed dendritic morphology. This is due to large temperature gradient between liquid iron and the casting surface at room temperature. High heat extension rate under such large temperature gradient leads to large super-cooling leading to numerous nucleus formation in thin liquid volume near the mould surface, which grow randomly leading to fine equi-axed structure. Soon the temperature of the casting surface increases and liquid temperature decreases, decreasing the temperature gradient. Consequently, G/R decreases that promotes columnar structure and it continues till the core of the liquid. Solidification rate increases sharply at the end of solidification which decreases the G/R to a very low value, promoting equi-axed dendritic structure.

Here I will demonstrate how R increases significantly at the later stage of solidification, by a heat balance. The Schematics of solid-liquid heat balance in the mushy zone is shown in the Figure 48.1.

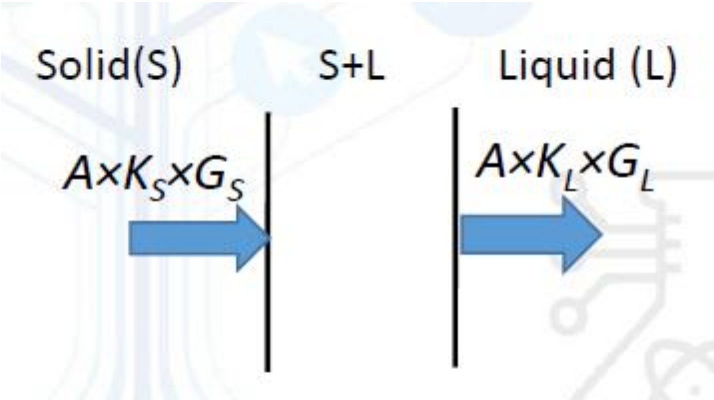

Figure 48.1: Schematics of heat balance in solid-liquid mushy zone

The heat balance statement is: heat entering the mushy zone from solid side + heat generated by solidification = heat leaving to the liquid. Mathematically, the heat balance may be represented by the equation 48.1.

$$\left(A\times K_S\times G_S - A\times K_L\times G_L\right)\times\Delta t=\rho_L\times f_L\times A\times\Delta r\times L$$
$$\Rightarrow R=\frac{\Delta r}{\Delta t}=\frac{\left(A\times K_S\times G_S - A\times K_L\times G_L\right)}{\rho_L\times f_L\times L} \quad (48.1)$$

Where, A, G_S, G_L, K_S,K_L,L,f_L, ρ_L,Δr represent the solid liquid interfacial area, thermal gradient on the solid side of the solid-liquid interface, temperature gradient on the liquid side of the solid-liquid interface, thermal conductivity of solid, thermal conductivity of liquid, frctional liquid in the mushy zone, density of liquid, and the thickness of the solidified shell, respectively.

From equation (48.1), it is seen that f_L lies in the denominator; so when f_L becomes very low at the later stage of solidification, R increases tremendously, decreasing G/R that promotes equi-axed dendritic structure. Besides, constitutional super-cooling also promotes such structure in alloy solidification.

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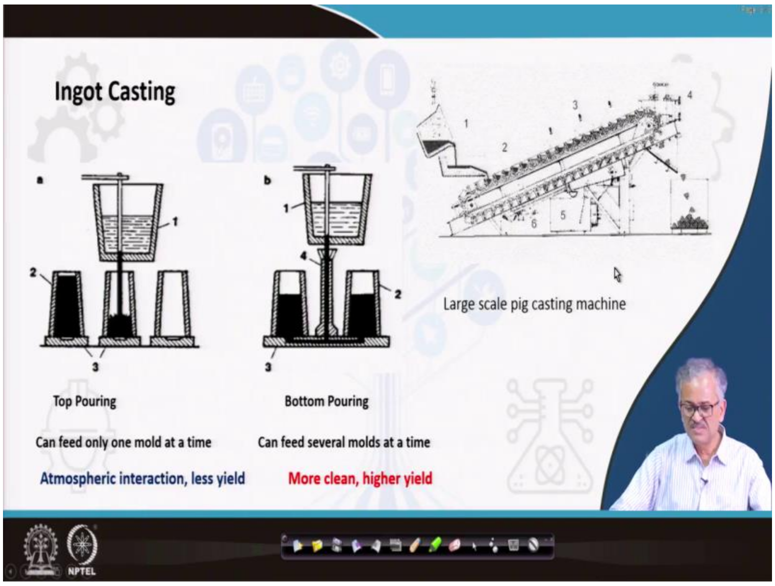

So, let us discuss the technology of ingot casting and associated defects. Two process technologies are available for making batch ingot castings (Figure 48.2). One is top pouring where liquid iron is poured in the ingot from the top and the other where liquid enter the mould from the bottom, called the bottom pouring.

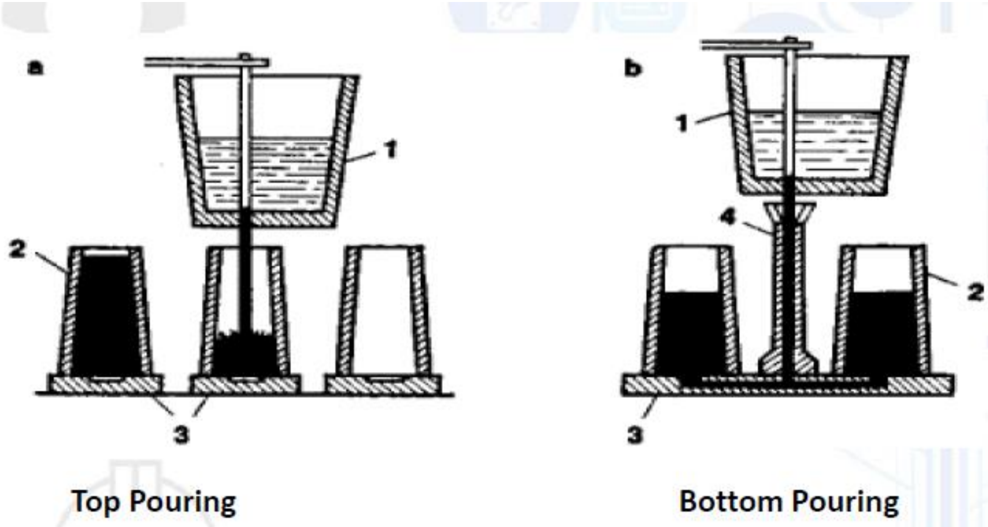

Figure 48.2: Schematics of top and bottom casting machine

In case of top pouring atmospheric interaction and surface turbulence makes the steel contaminated with oxygen and nitrogen. Besides, the last liquid to solidify resides at the top, which undergoes shrinkage at the end of solidification yielding piping (shrinkage cavity) at the top. Often such pipe penetrates significant distance below the top surface. Such exposed pipe surfaces get oxidized and ingot portion containing the pipe needs to be chopped off, causing large yield loss.

In case of bottom pouring liquid enters from the bottom and liquid rises from the bottom smoothly without causing much turbulence and that causes less atmospheric interaction. Besides since liquid is fed from the bottom top shrinkage and pipe is not formed that eliminates top pipe cutting and loss of yield. In case of bottom pouring a number of moulds could be fed at a time.

Figure 48.3 shows the top poured large scale pig casting machine.

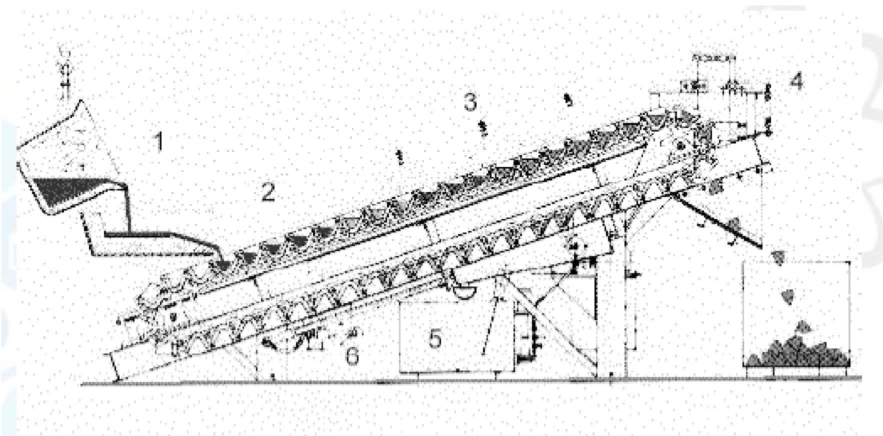

Figure 48.3: Large scale pig casting machine.

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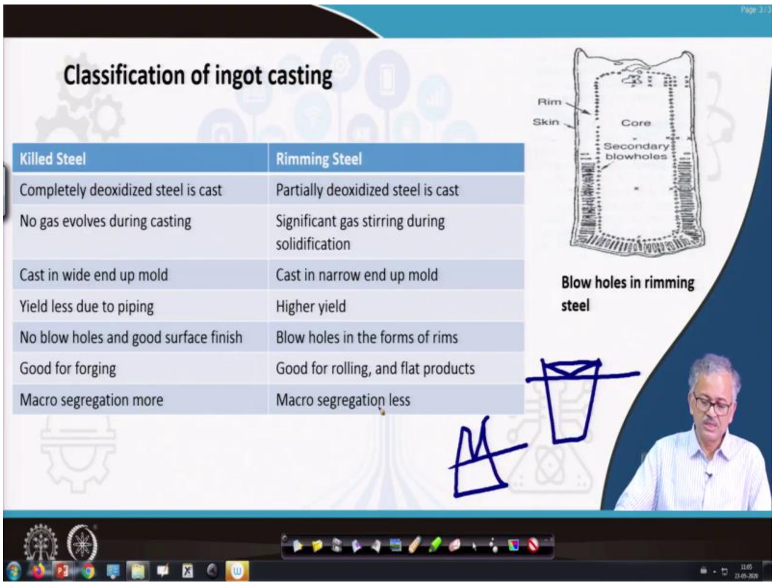

Now, let us discuss classification of ingot casting. Two types of castings are there; one is called the killed steel and another is called the rimming steel. In case of killed steel completely deoxidized liquid steel is cast, with no gas evolution (in absence of residual oxygen in the bath) during solidification.

In case of rimming steel, partially deoxidized steel (keeping certain amount of residual oxygen in the bath before solidification) is cast that leads to large CO gas evolution during solidification, intensely stirring the liquid.

In killed steel in absence of gas evolution and stirring in the bath, various patterns of macro segregations exists (Figure 48.4). However, there exists mild convection in the ingot due to natural convection and the rejected solute during solidification are carried and deposited the solidified structure in the form of A and C type of macro-segregation. The solute depleted liquid deposits at the bottom forming negative segregation.

In case of the rimming steel, no macro-segregation forms due to intense bath agitation. But, evolved gases are entrapped into the solidified structure in the forms of blowholes as primary and secondary rings Figure 48.5). However, such embedded blow holes are welded by rolling operation and therefore rimming steel are suitable for producing flat products. O the contrary due to nice surface finish and no blowholes, killed steel are suitable for forged products.

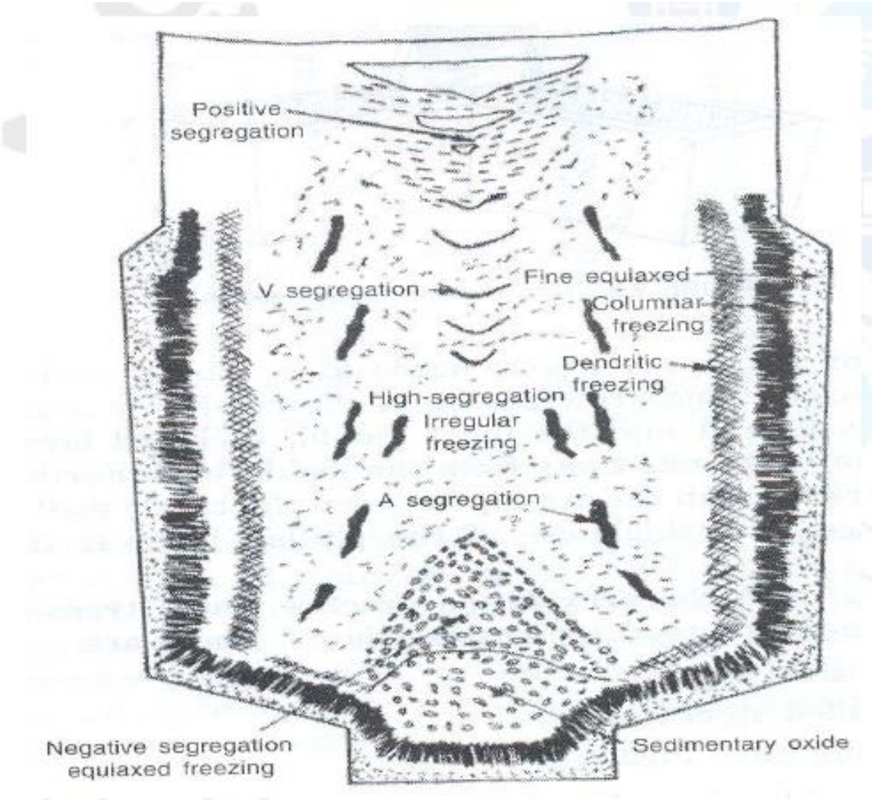

Figure 48.4: Schematics of macro-segregation in killed steel

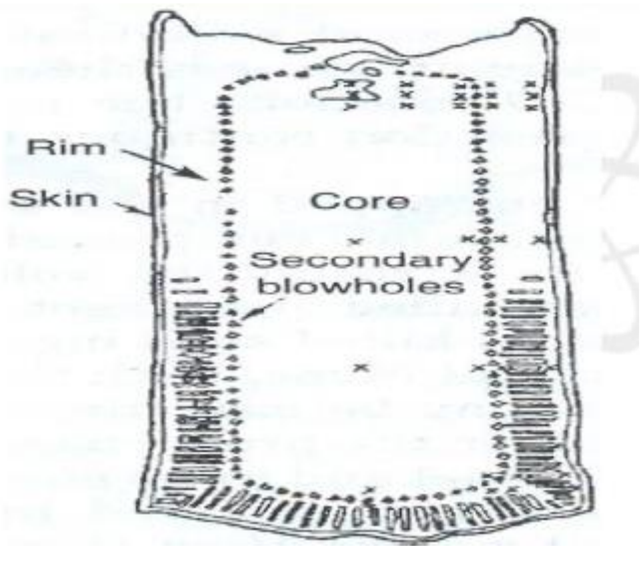

Figure 48.5: Schematics of blow holes in rimming steel

Killed steel is usually cast in a wide end of mold which results in shallow shrinkage pipes or cavity increasing the yield. Similarly, rimming steel is cast in narrow end up mould, which restricts the gas release from the top and intensify the bath stirring.

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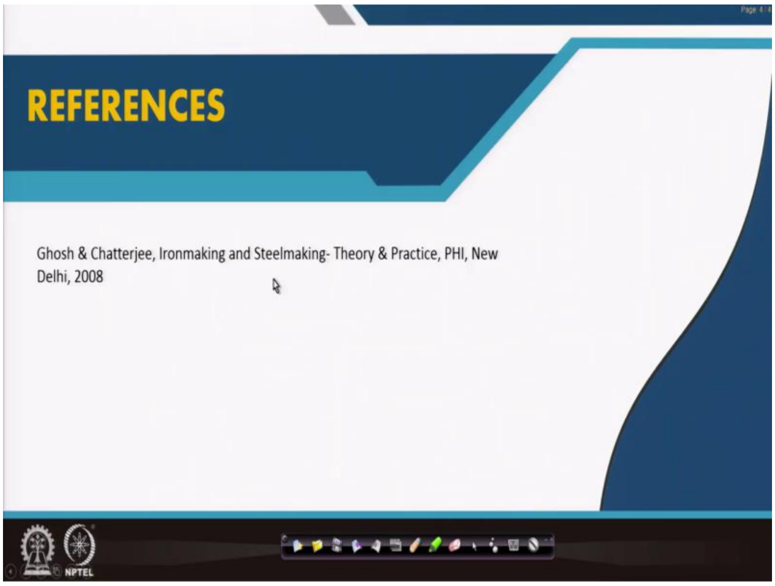

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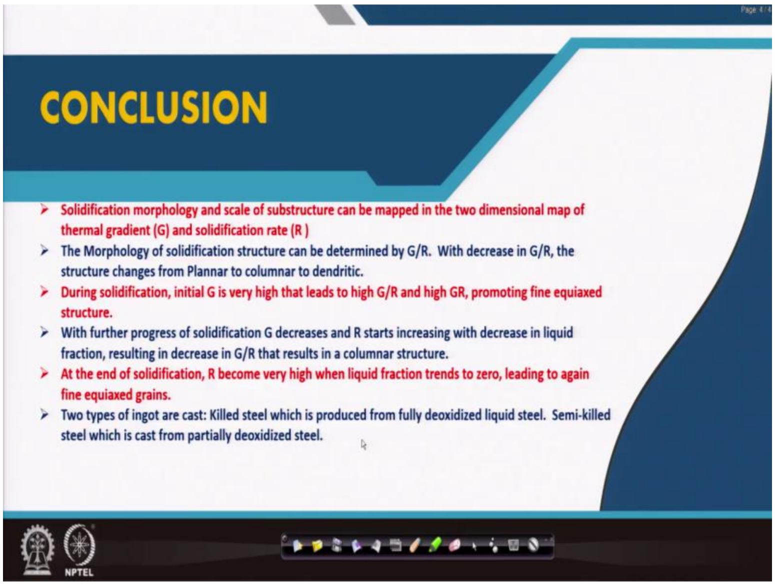

Conclusion: Solidification morphology and the scale of solidification structure can be mapped into two dimensional domain of thermal gradient and the solidification rate. The morphology of solidification structure can be determined by G/R, where the GR defines the scale of solidification structure. The morphology of cast structure follows a fine equiaxed structure at the skin followed by columnar zone and finally equiaxed dendritic structure at the core. The fine equiaxed structure at the skin is due to initial high temperature gradient, high undercooling that promotes large nucleation and equiaxed structure. Subsequent to the skin formation, temperature gradient and G/R decreases promoting columnar grain. At the later stage when liquid fraction become less, solidification rate increases sharply leading the equiaxed structure at the core and in case of alloy steel, constitutional supercooling also aids formation of equiaxed dendritic structure at the core.

Ingot may be cast by top pouring or bottom pouring. Ingot cast by bottom pouring are more clean, has higher yield.

Two types of ingots are usually cast: killed steel and rimming steel. Killed steel are cast in wide endup mould from fully deoxidized (killed) steel; whereas semikilled steel are cast in narrow endup mould from partially killed steel. Killed steel contains macro-segregation but has nice surface finish and is suitable for forging product. Semi-killed steel does not contain any macro segregation but contains entrapped blow holes in the form of rings and are suitable for flat product.