Iron Making and Steel Making

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Module – 10
Lecture – 46
Casting fundamentals - Heat Transfer

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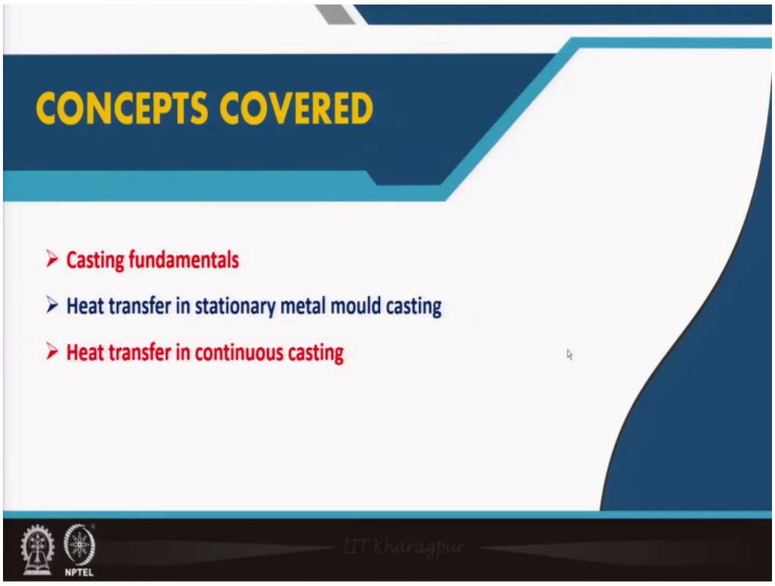

In this lecture we will discuss heat transfer in casting-one of major the Casting fundamentals. Topics covered will include heat transfer in stationary metal mould casting and heat transfer in continuous casting.

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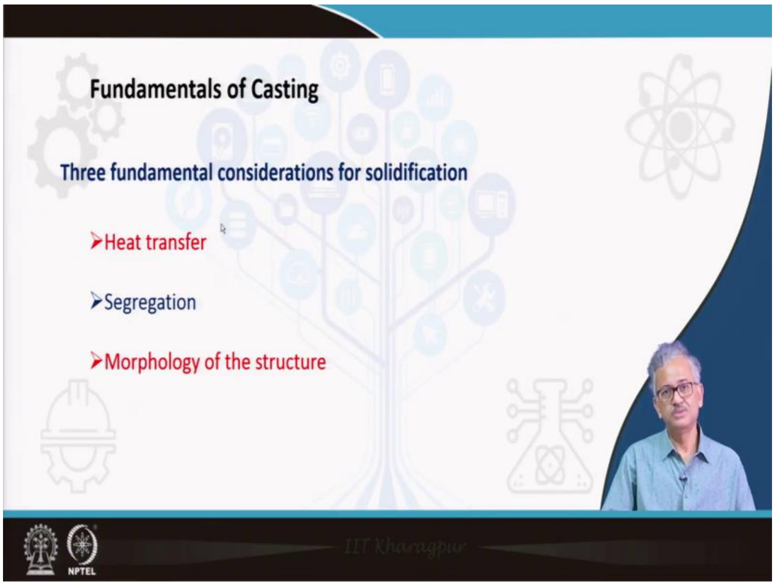

Three major fundamental considerations in casting that are heat transfer, elemental segregation and morphology of solidified casting. All these topics will be covered through quantification in separate lecture.

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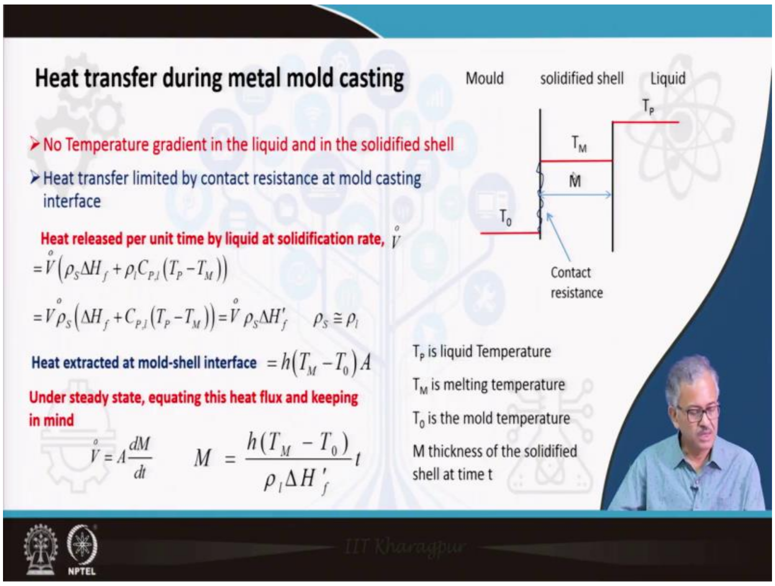

Now, let us discuss how to quantify the thickness of solidified shell during casting. I am just directly coming to the metal mold casting, because most simple and faster casting routes like ingot and continuous castings are carried out in the metal mold. In the foundry customized complicated casting are carried out in sand mold; but we are not discussing sand mold casting.

So, first we will develop a very simplified model in a metal mold casting, assuming there is no temperature gradient in the liquid as well as in the solidified shell, as shown in Figure 46.1.

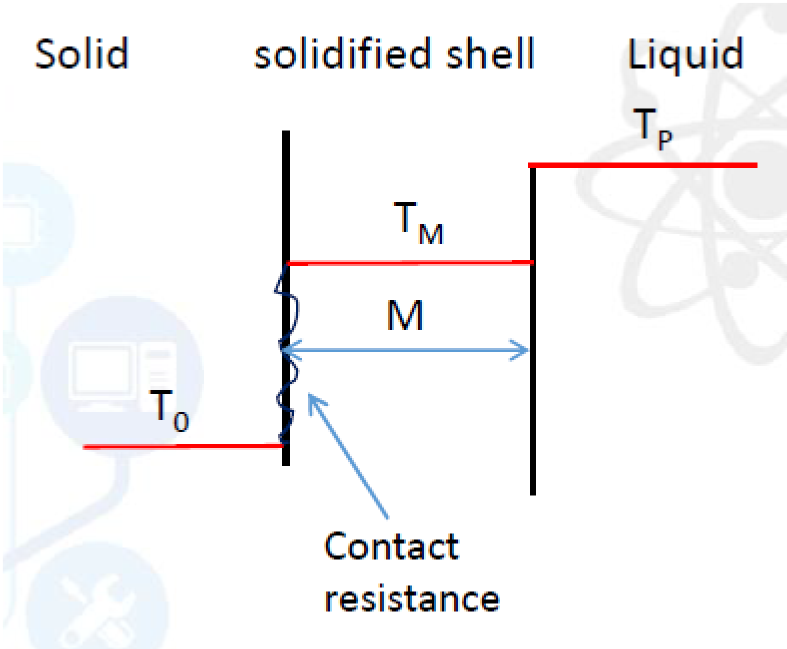

Figure 46.1 Schematics of simplified temperature profile

T_P and T_M represent the liquid temperature and melting temperature of the steel being cast. T_0 is the mould temperature. A sharp drop in temperature at solidified shell and mold interface is due to contact resistance there. To avoid welding of solidified shell with the mold wall, flux powder is used as lubricant, which on heating creates voids that separate the solidified shell from mold interface.

Now the heat balance statement is: Heat generated during solidification per unit time = heat that departs to mold per unit time through shell-mould interface. Heat generation has two components: i) sensible of liquid steel that is released during its cooling to melting temperature, ii) the latent heat during solidification. Heat released during solidification at a rate $\dot{V}$ is given as:

$$= \dot{V}\rho_S\left(\Delta H_f + C_{P,l}(T_P - T_M)\right) = \dot{V}\rho_S\Delta H_f' \tag{46.1}$$

Where, $\Delta H_f' = \Delta H_f + C_{P,l}(T_P - T_M)$, also density of solid and liquid of steel are assumed to be equal.

Heat extracted at the mold-shell interface is given as:

$$= hA(T_M - T_0)$$

(46.2)

Where h represents the heat transfer coefficient at the shell-mould contact.

Equating equations (46.1) and (46.2) and keeping in mind, $\dot{V} = \frac{dM}{dt}A$, where M is the solidified shell thickness at time t and A is the interfacial area between solidified shell-mould interface, and subsequently integrating from time 0 to t when the shell thickness grow from 0 to M, the resulting equation becomes:

$$M = \frac{h(T_M - T_0)}{\rho_l \Delta H'_f} t$$

(46.3)

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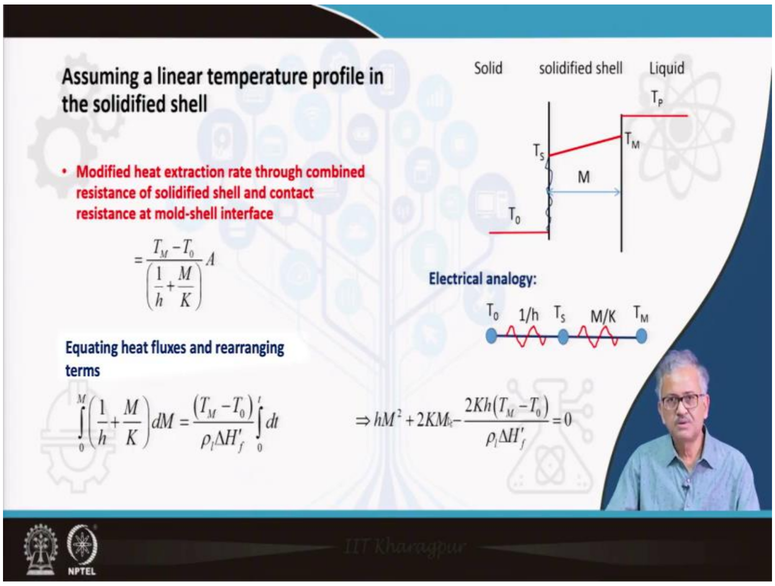

Let us make the above model little complex and more realistic by assuming there exists a linear temperature profile in the solidified shell. It is likely that solidified shell will also offer a resistance to heat transfer. So, new temperature profile may be as shown in Figure 46.2.

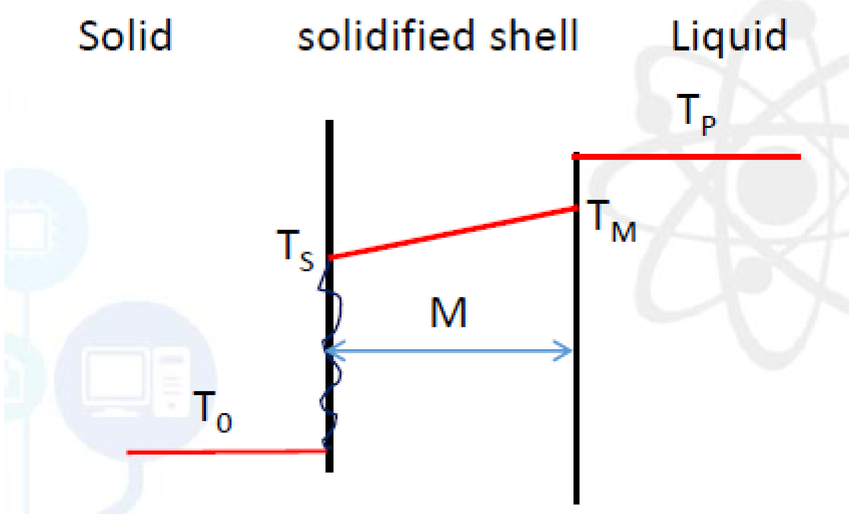

Figure 46.2: Schematics of temperature profile with a linear profile in the solidified shell.

Now, there are two resistance in series one at the shell-mould interface and other in the solidified shell; the electrical analogy of which may be represented as:

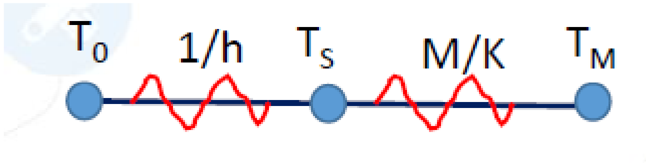

Figure 26.3: Schematics of electrical analogy of electrical resistances in the mold and solidified shell

So, heat balance statement under this condition may be mathematically represented as:

$$\frac{(T_M - T_0)}{\left(\frac{1}{h} + \frac{M}{K}\right)} = \rho_S \Delta H_f' \frac{dM}{dt}$$

(46.4)

Rearranging and integrating between t=0 to t

$$\int_0^M \left(\frac{1}{h} + \frac{M}{K}\right) dM = \frac{(T_M - T_0)}{\rho_l \Delta H_f'} \int_0^t dt$$

(46.5)

Finally the integral form may be expressed as:

$$hM^2 + 2KM - \frac{2Kh(T_M - T_0)}{\rho_l \Delta H'_f} = 0$$

(46.6)

The thickness of the solidified shell may be obtained as from the solution of quadratic equation. Obviously, solution 46.3 is straight forward and handy.

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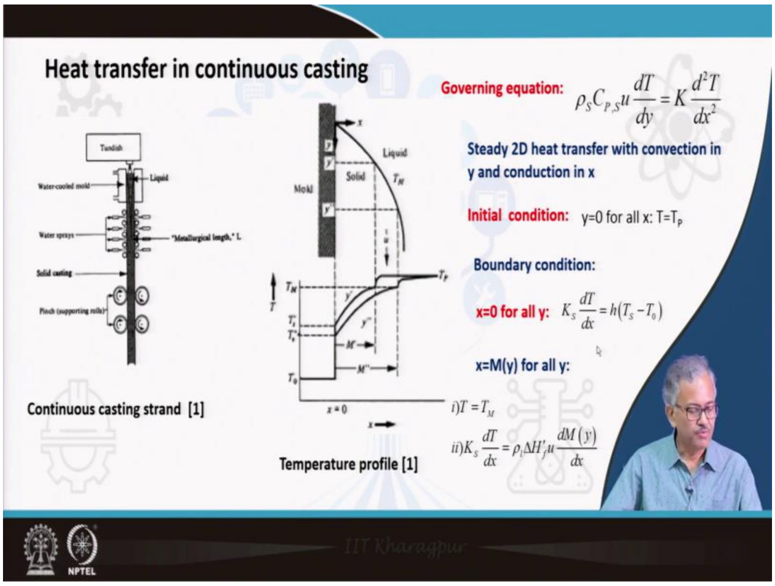

Now, let us consider heat transfer during continuous casting. Heat transfer in the continuous casting is little different, because metal is cast at a continuous rate. And, when the casting comes out of the mould, it is not completely solidified; it only develops a skin thickness and liquid remain in the core, which subsequently solidify in the secondary cooling zone by water spray.   The schematics of continuous casting is shown in the figure 46.3.

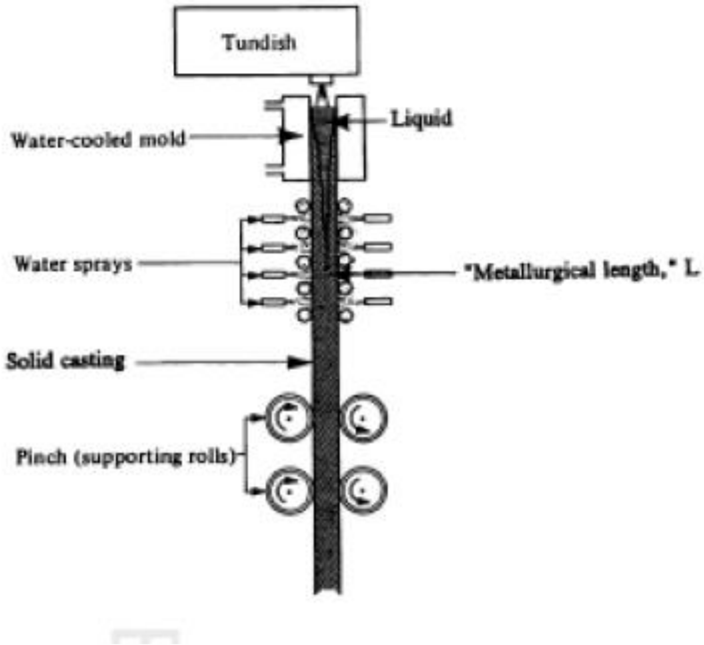

Figure 46.3: Schematics of continuous casting

The temperature profile looks like as follows:

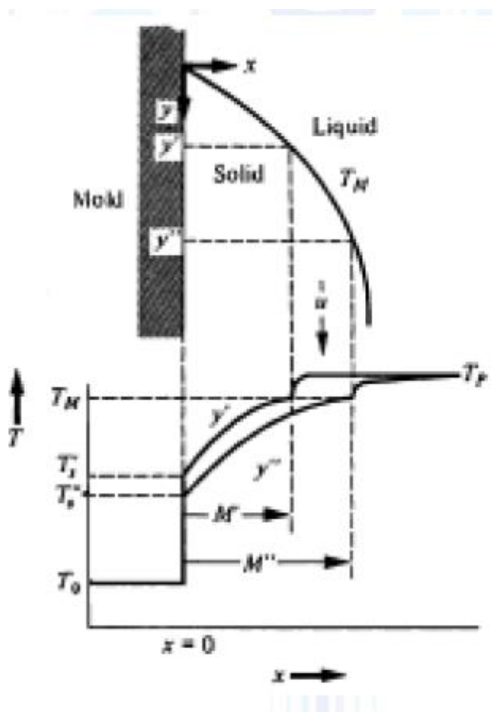

Figure 46.4: The temperature profile in continuous casting mould

The temperature profile is parabolic due to vertical movement of casting. Also the surface temperature decreases with increase in depth below the liquid meniscus. Also the shell thickness increases with increase in distance below the liquid meniscus. Calculation of skin thickness is important, because if skin of appropriate thickness is not develop at mould exit, the skin will break and liquid will come out.

Since the casting is moving at a constant velocity another mode of heat transfer, i.e., a convection term appears in the model formulation, with respect to a stationary observer. In a fixed control volume on casting space, material will enter and exit control volume at constant casting speed. So, the governing equation will be two dimensional steady state equation with heat diffusion in x-direction and heat convection in y-direction as follows:

$$\rho_S C_{P,S} u \frac{dT}{dy} = K \frac{d^2T}{dx^2} \tag{46.7}$$

Where, u is the casting velocity and K is the thermal conductivity.

Initial condition may be given as:

$$y=0 \text{ for all } x: T=T_P \tag{46.8}$$

Boundary conditions:

Flux continuity at shell-mold interface:

$$x=0 \text{ for all } y: \quad K_S \frac{dT}{dx} = h\left(T_S - T_0\right) \tag{46.9}$$

At shell liquid interface, two conditions exists: i) temperature is melting temperature, ii) heat released by solidification will move into the mold.

x=M(y) for all y:

$$i) T = T_M$$

$$ii) K_S \frac{dT}{dx} = \rho_l \Delta H'_f u \frac{dM(y)}{dx}$$

(49.10)

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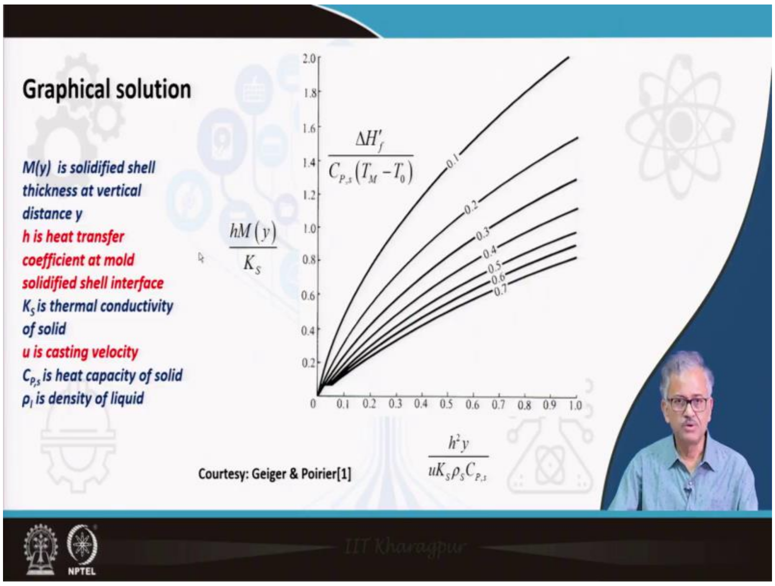

The graphical solution of the above problem (equation 46.7 to 46.10), may be given as:

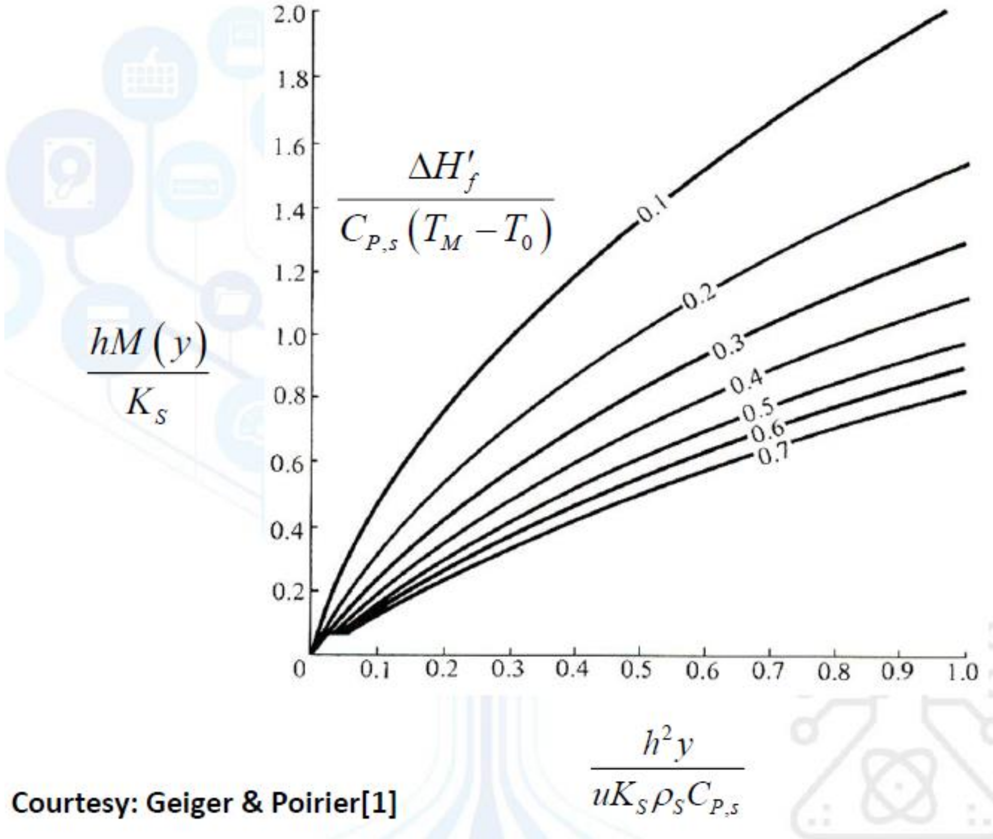

Figure 46.5: Graphical solution to calculate the exit skin thickness from concast mould

The solution is given in terms of relationship between three dimensionless numbers. Dimensionless skin thickness ($\bar{M}$), dimensinless y-distance ($\bar{y}$), and dimensionless modified latent heat of fusion$\left(\overline{\Delta H_f'}\right)$ as given:

$$\bar{M} = \frac{hM(y)}{K_S}$$

(49.11)

$$\bar{y} = \frac{h^2 y}{uK_S\rho_S C_{P,S}}$$

(49.12)

$$\overline{\Delta H_f'} = \frac{\Delta H_f'}{C_{P,S}(T_M - T_0)}$$

(49.12)

So these relationship could be used to calculate the skin thickness at the mould exit. Dimensionless distance at mould exit can be found using equation (49.12) putting y = L= mould length. Knowing the thermos-physical properties of casting material, pouring liquid temperature and mold temperature, the dimensionless modified latent heat of fusion could be calculated. Then using these two parameters and the Figure 46.5, the dimensionless exit thickness could be obtained, which subsequently will yield the dimensional exit thickness.

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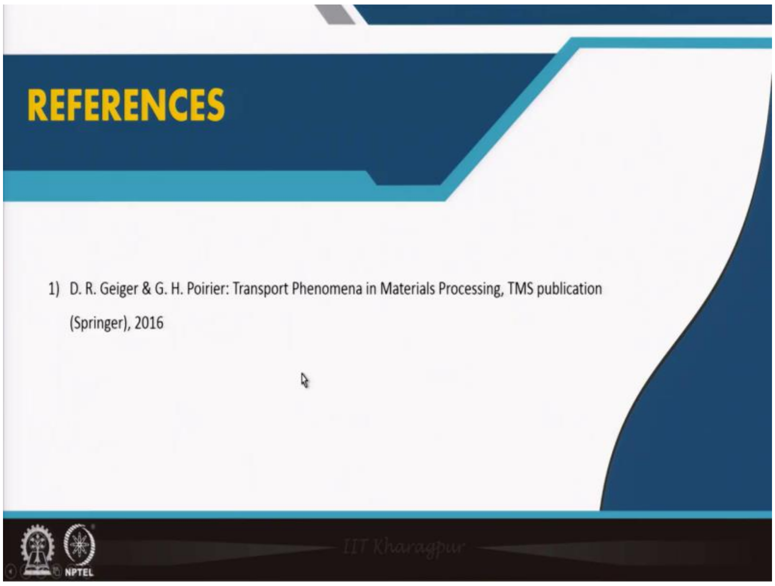

Major reference is Geigar and Poirier: Transport Phenomena in Materials Processing.

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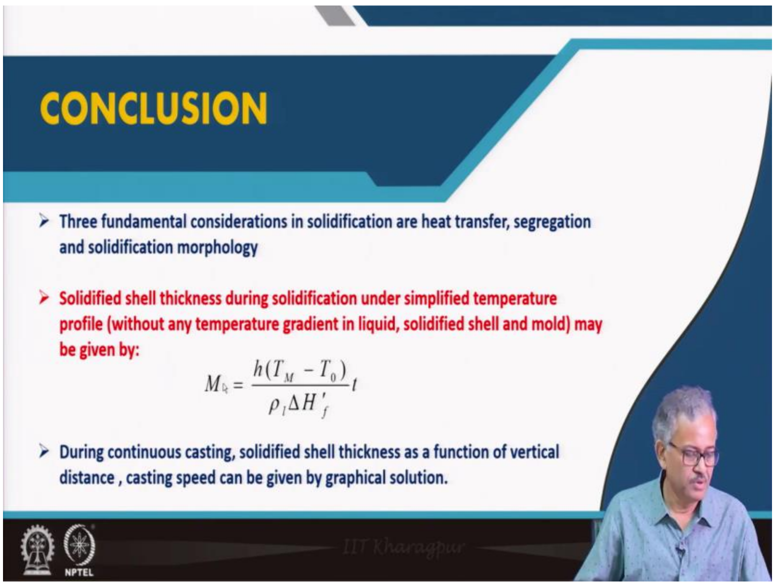

Conclusion: Three fundamental considerations in solidifications are heat transfer, segregation and solidification morphology. In this lecture we have covered heat transfer in metal mould casting, both for ingot casting as well as for continuous casting. The major aim have been to find out the solidified shell thickness at a particular instant.

For fixed metal mould casting, such correlation has been obtained based on assumed temperature profiles. The most solidified temperature profile considered without any temperature gradient in liquid, solidified shell and in the mould. Under this condition, heat balance yields the most simple and handy correlation, given by equation 46.3.

Another quadratic correlation-ship between M and t has been obtained by considering a linear temperature profile in the solidified shell, given by equation 46.4.

For continuous casting, since the casting is not stationary, a more rigorous analytical solution is used to estimate the skin thickness at the mould exit. It is to be noted that during continuous casting at the exit of the mould, the casting is not completely solidified. Only a skin forms on either sides with liquid inside. The skin thickness at the mould exit should be sufficient that can withstand the ferro-static head inside and does not break.