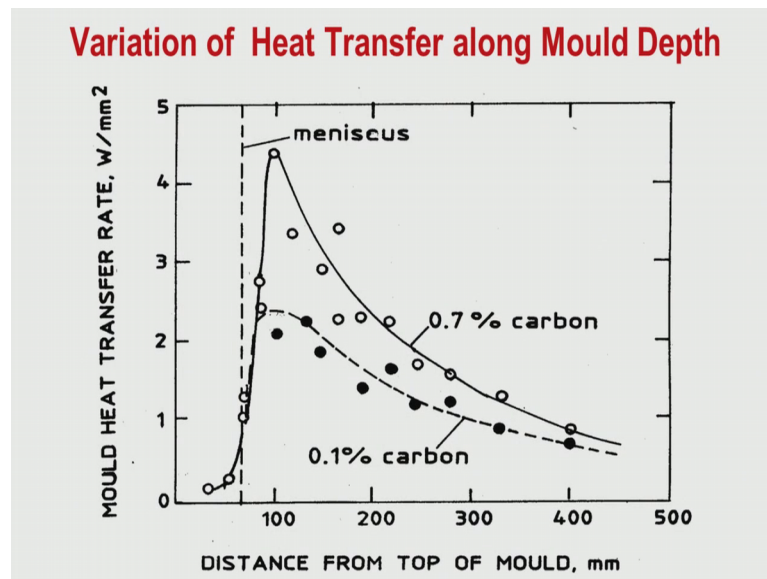


Steel Quality Role of Secondary Refining and Continuous Casting
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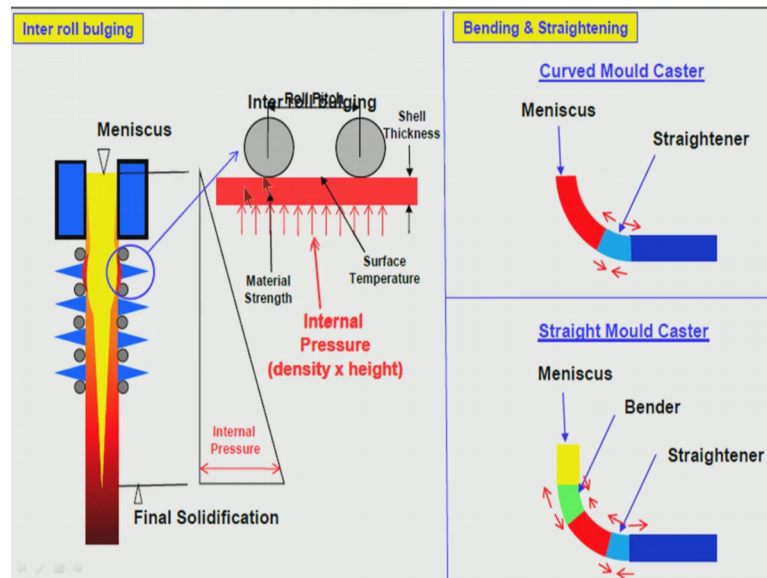
Module - 05
Lecture - 23
Heat Transfer in Mould

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This is another issue which we should know: how the heat transfer varies along the mould depth. This is distance from the top of the mould you know you possibly you know that within the mould.

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Just look at the meniscus is just not at top of the mould we will try to understand why it is not so, because otherwise you know there may be you know when there is oscillation this liquid steel everything might come out. So, that is not desirable. So, this meniscus level is at certain depth from the mould top.

So, when the in that figure I will show the mould top; that means, these portion is 0 and we are coming down the mould. So, this is what is important. So, along the mould depth how the heat transfer is changing that is what I we want to show here. So, this was the mould top. So, the meniscus level is somewhere here, this is the meniscus it is not at 0 position it is certain at a depth say may be 70 millimeter or. So, this is in millimeter distance from top of mould.

So, at the meniscus level you know what is happening; that means, the heat transfer strand here that is this is basically heat transfer along mould depth and heat transfer the horizontal heat transfer. That means, how the heat is extracted from molten steel to the mould I am talking of that heat transfer is not a vertical heat transfer.

In the mould is the mould top. So, it is the across the mould I am talking of this heat transfer. So, this heat transfer is somewhere trying to increase here and it is at a peak at a certain depth from the meniscus why? Because at the meniscus what do you have? It is just the shell is trying to form if the shell is very thin, you know there might be some contraction so; that means, there will be air gap. So, air gap controls the heat transfer.

So, the peak of the heat transfer is at a certain distance from the meniscus may be 30 millimeters or so, may be at a depth of 100 millimeter from the top of the mould. So, from the meniscus is around may be 30 millimeter. So, the peak of the heat transfer is somewhere here, and then what it has it is showing is two different steel one is the 0.7 percent carbon and it is a 0.1 percent carbon.

As I was telling you the steel grade place have very important role in heat transfer. This slowly will try to understand why it happens. So, 0.1 percent carbon if you look at it, the heat transfer is relatively less. Not only the peak of the heat transfer also, but along the mould also it is relatively less compared to 0.7 percent carbon. Why it is so, we will understand later, but I will just giving you a hint 0.1 percent carbon is a depression type of grade. That means, the surface you get lot of depression, and 0.7 percent carbon it is not a depression type of grade because some other reason I will come to it later there is a mould of sticking. So, you have the shell trying to move towards the mould. So, there is hardly any gap between the mould and the shell except the gap of the slag layer.

So, that is why relatively we have more heat transfer about 0.7 percent carbon. In fact, if you plot the similar car for say 0.02 or 0.03 very low carbon, it is similar to 0.7 percent carbon, because there also the shell will not be will try to stick towards the mould. So, the heat transfer will be more relatively compare to 0.1 percent. 0.1 percent carbon that is we call it a peri technique if you remember the peri technique reactions starts at 0.1 percent carbon.

So, this 0.1 percent carbon is called the peri technique composition. So, it is just the beginning of the peri technique reaction, but it is called peri technique you know composition because of some other reason I will come to it later on because this particular composition around 0.1 percent carbon, will be having lot of surface defects called depressions. So, that is why the heat transfer is relatively low for 0.1 percent carbon.

And why this heat transfer comes down? You know along the mould because as the shells becoming more and more thick, naturally there is some less amount of heat transfer is needed number 1. Number 2, the heat transfer also gets lot of resistance because of the thicker shell; number 3, is at the shell is increasing there is a more probability of the shell getting contracted. So, that is why also there will be some air gap

formation. So, all these factors will lead to the heat transfer coming down from the top of the mould to below the mould.

Finally when you are coming out of the mould then it is no longer the heat transfer in the mould, but that is called secondary heat transfer. The heat transfer there is still less because you know more thick shell has found. So, naturally you do not require so much of heat transfer, the heat required to be transferred from the inside the you know liquid pool comes down. So, this is very important the heat transfer variation from the top of the mould to the bottom of the mould how does it change this is very important to understand.

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Cast Structure

- Alloying elements are rejected from solid to liquid during solidification , segregation makes liquid rich with solutes
- Solidification starts as a plane front , but soon changes into **dendritic type** , because of **constitutional supercooling** of **segregated liquid adjacent to solid-liquid interface**
- Initially dendrites grow in **specific primary direction**, and subsequently **secondary and tertiary dendrites** form
- Three zones exist during the stage of solidification : **Solid shell** , Mushy zone (**solid + liquid**) , Liquid pool

Macro cast structure : Columnar at surface + central equiaxed
% Equiaxed is relatively large with low superheat and EMS

Now, let us try to understand heat transfer is basically doing what? Heat transfer is helping in the solidification. So, heat transfer will definitely control the cast structure. So, let us try to understand how the cast structure is all being, what is the cast structure, what is the shape size of the cast structure. This alloying elements in steel you will have lot of alloying elements; you may have carbon you may have sulphur phosphorous silicon manganese other alloying elements. All alloying elements because of segregation they are rejected from solid to liquid. This I will issue, I will take up in more details later on.

Let us try to understand these alloying elements are rejected from solid to liquid during solidification. All alloying elements are rejected there is no alloying element which will

be you know more in solid unless in liquid the concentration will never happens. So, all alloying elements are rejected from solid to liquid, the solid will have solubility less solubility for all alloying elements, the solid will be having less of the less concentration of the alloying elements liquid will be having more. So, it is getting rejected as the solidification progresses. So, liquid is becoming more and more rich in the alloying elements. So, this is what is I am telling segregation makes liquid rich, rich with solutes.

So, what is the implication of this? Implication is the liquid steel which is adjacent to the solidification front, which is the temperature of the liquid is slightly lower because of what? Because you know it has become rich in the solutes. So, the solidification temperature is lower; because of this and because of this we call it this is we call it constitutional super cooling because it is super cooling is happening not because of heat transfer, but because of segregation. So, whenever super cooling is happening because of constitutional super cooling is called it is called constitutional super cooling, because this super cooling. Super cooling basically means the temperature of the liquid adjacent just in front of the solid liquid front. So, its surface is getting cooled because of segregation. So, this is called constitutional super cooling.

But because of this the solidification front which was initially plane front, it changes into dendritic this is very important. Why dendrite forms? Dendrite forms if you have a single pure element if you have solidifying it, you will not have dendrite you will have a plane solidification front. Dendrite is occurring or forming because of segregation. Please try to remember because there is segregation there will be constitutional super cooling, and because of this you have dendrite; that means, tree like formation in a particular direction it will grow. So, this is important to understand.

Then initially these dendrites are growing in specific primary direction, in which direction which will grow? It will try to grow in the direction wherever there is heat transfer number one; number two in the crystal the direction typical directions say 1 0 0 in those directions this dendrites will grow in cubic you know crystals.

So, these initial dendrites grow in specific primary direction, subsequently you have secondary and tertiary dendrites along other directions. So, you have primary dendrites which are more long and then you have and almost at the you know perpendicular

surface direction you have secondary dendrites and again to the perpendicular of the secondary dendrites you have some tertiary dendrites.

So, this is very important to understand why you have solidification through dendrites because you have segregation, because we are casting alloy we are not casting a single element, here the solidification is taking place of an alloy. So, there are lot of solutes in it all those solutes are enriching the liquid, because of this the solidification temperature of the liquid is coming down it is becoming relatively cool. So, it is called constitutional super cooling and because of constitutional super cooling you have a dendritic solidification front and not a plane front. Its starts with a plane front solidification, but immediately get into a dendritic form. So, dendrites start shooting out from the solidification front.

And I have told as I have told initially dendrites grow in specific primary direction and subsequently we have secondary and tertiary dendrites. Now please try to understand what is happening during solidification. You have a solid shell which has solidified, you of course, have liquid from which the solid shell is forming and then you have a mushy zone, what is mushy zone? It is a combination of solid plus liquid what way the portion of the liquid which has already got solidified. So, this 100 percent solid.

So, here fraction of solid is 100, in the liquid the fraction of solid is 0 and in between in the mushy zone you have intermediate; that means, from 0 fraction of solid you are going to 100 percent of solid during solidification, and in between you have a mushy zone its called mushy because you have solid liquid both. This is very important this mushy zone will dictate you know quality of the solid, quality of the solid shell which is forming. So, we have to deal with it in a greater detail subsequently.

So, please try to remember during solidification one solidification over here only solid before solidification we have only liquid, but during the stage of solidification you have three areas solid shell mushy zone liquid pool. Now, another thing I have mentioned here, what is the macro structure of the whole solid; that means, when solidification is complete you have only solid. So, you have columnar zone this dendritic columnar zone at the surface and then central equiaxed at the interior. Why this forms there are different reasons you know, but initially as I have told solidification you have columnar. Some people tell, but the very instance of initial solidification there may be certain equiaxed

zone at the surface, which is called chill zone the basically there is chill zone, but it is very very narrow.

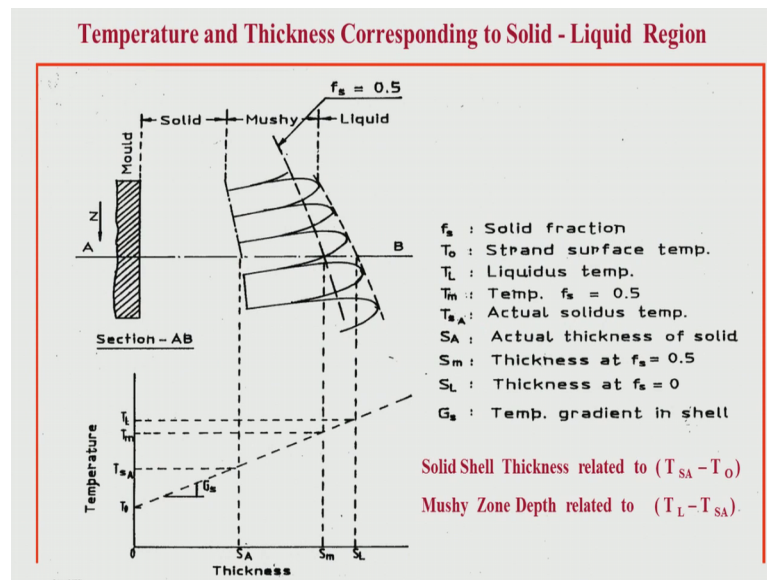
So, virtually after this chill zone you have columnar. So, sometimes the chill zone you cannot even see, it is so narrow. So, basically you have two broad zones, one is the columnar and it is the dendrites in columnar fashion growing in a columnar they called columnar zone at the surface. And finally, in the equiaxed they there also dendrites, but they are equiaxed, here it is columnar the difference is between the shape of the dendrites.

Now, how much is percentage equiaxed, how much is columnar in a cast structure is dictated by superheat and use of electromagnetic studying. You know superheat because what is superheat, superheat basically the difference between the actual liquid temperature during casting and your melting point now liquid as temperature. So, normally it is slightly higher than liquid. So, it is called the superheat.

Now, in the last session I have talked about the superheat because you know in connection with it was in connection with you know cleanliness of the cast structure I have talked about. If superheat is very low then you know cleanliness is slightly affected, but if the superheat is low, you have more of equiaxed zone rather than columnar zone which is desirably is columnar should be less more of equiaxed should be there equiaxed means directionality of the properties are not there during rolling and during processing things will be better to roll easier to roll there will not be any crack formation, but if you have columnar there is a possibility of quality issue during hot rolling.

So, lower superheat helps in having less columnar and more equiaxed number one another thing is electromagnetic studying what is electromagnetic studying. Normally when casting is taking place you know the liquid steel is not start liquid steel is stable, but you can start the liquid steel using some starrer during some continuous casting. When the solidification is as not got completed; that means, it has started these are not completed then there is some liquid. So, that liquid if it is start, you get final structure you get final grades final solid grades fine.

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So, you have got more of equiaxed grades less of columnar grades. So, low superheat and electromagnetic studying these two are useful for having relatively more equiaxed and less of columnar. As I was discussing you know when solidification is taking place what is happening. You have a solid shell this is the mould. So, you are going away from the mould. So, you have a solid shell you have a mushy zone you have liquid. So, liquid is naturally away from the mould. So, heat is getting transferred from the liquid to into the mould, solidification is taking place you know this is not complete; so solid shell, mushy zone and the liquid.

So, here you know solid fraction f_s is 1 or 100 percent, and the liquid front it is 0 in between we have some solid fractions. So, this is the 0.5 line just to indicate; what is the 50 percent solidification front. So, this how what is the you know relative thickness of the solid in the mushy zone is dictated by here I have shown the temperature, these issue I will be up later on just to indicate what is during the time of solidification what is the relative thickness of solid shell in the mushy. In certain grades you have during the time of solidification thick solid shell and thin mushy zone, but in certain grades you have thin solid shell and void mushy zone where you have more problem.

So, it is dictated by what please try to look at these temperatures. This is T_0 is the temperature on the solid shell. So, temperature surface temperature which is very low may be 50 degree centigrade, 100 degree centigrade. The solid which has become solid

long back and it is getting cool also. So, it is relatively less may be 100 200 whatever it is. This is what is this temperature, when the solidification starts this is the actual solidus temperature not equilibrium, I have given here the actual solidus temperature TSA. So, this point corresponds to actual solidus temperature.

What is this temperature this is TL; that means, liquidus temperature. So, the difference between the liquidus temperature and actual solidus temperature will dictate; what is the mushy zone depth. Lower the actual solidus temperature more void will be the mushy zone that is why segregation place. So, important roll what segregation is doing? More the segregation more is the more depression is solidus temperature, but that the solidus temperature will be more depressed more is the segregation.

So, the roll of segregation is to depress the solidus temperature, why you I have discussed this later? Because the liquid which is solidifying subsequently later on later on is getting more and more rich in the solutes. So, the solidus temperature is getting more and more suppressed depressed.

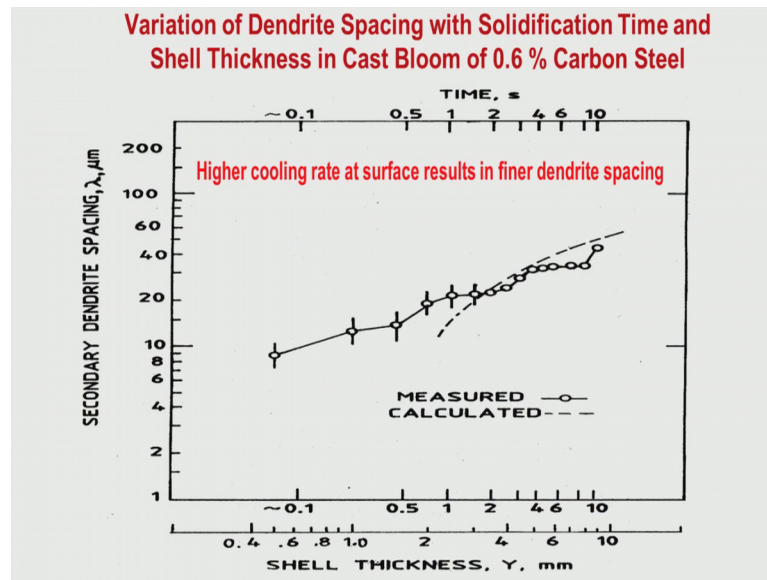
So, what is happening? The gap between the liquidus and the solidus is increasing; if this gap increases then the depth of the mushy zone also will increase please try to remember this. Whole idea of doing this is to drive on the point, the mushy zone thickness and the solid shell thickness when solidification is taking place is dictated by the liquidus temperature and the actual solidus temperature. I have shown here solid shell thickness it depends on related to the actual solidus minus the surface temperature. Mushy zone depth related to difference between the liquidus and the actual solidus.

So, what is segregation doing? Segregation is depressing the actual solidus; by depressing the actual solidus this TSA is coming down that means the difference between TL and TSA is increasing. So, more is the difference mushy zone become more deep and solid shell become more thin; that means, at the time of solidification you have thin solid shell void mushy zone because of segregation.

And now this segregation I will when I discuss segregation I will it will be more clear to you, this segregation depends on the extent of segregation depends on the solute elements like sulphur, phosphorous, boron these elements they create more of segregation. The reason is known because the k value you know the distribution coefficient is very low for this elements. Not only that this distribution coefficient is also

different between delta and gamma; that means how solidification takes place also influence the level of segregation. So, that will also influence the level of this change in actual solidus. So, that will also influence the depth of mushy zone, the mushy zone will be increased or decreased solid shell will be increased or decreased depends on that.

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So, these are very important issues to remember. So, let me discuss another important issue that with heat transfer I have told that with heat transfer the dendrite size the size of the cast structures. So, cast you know dendrites there changes how does it change. So, solidification you are starting the solidification, I have told you at the start of the solidification relatively heat transfer is very relatively high. Heat transfer is high means what is going to happen that is dendrites which is forming, they are relatively of a particular size when you are going to; that means, the surface is relatively final dendrites when you are going to inside; that means, the heat transfer. As you are going inside means what the heat transfer is changing with time solidification time heat transfer is increasing heat transfer is rather decreasing; that means, heat transfer is becoming more and more slow.

So, the size of the dendrites also will increase. So, this is the actual measurement, this is measured this is dot ones and this is the calculated this through modelling one has calculated. So, what is happening? So, dendrites size are secondary dendrites size are set

10 microns at the surface and after a time of say 10 seconds or say at a shell thickness of say 10 millimeter, you will find dendrites are say about 50 millimetre.

So, you see these are log scale. So, see what is happening. At surface dendrites are quite fine 10 millimeter 10 microns sorry 10 micron in size, and at a depth of say 10 millimeter; that means, after a solidification time of 10 seconds what is happening it is increasing to as high as 50 to 60 micron. So, the dendrites spacing that means, this is secondary dendrites.

Normally it is the secondary dendrites a spacing as measured to understand what is the dendrite size not the primary dendrites. So, this is dendrites spacing has been plotted λ , λ is the dendrites spacing in the micron micro meter. And this way this horizontal surface is idle the time or time is relative to the shell thickness I have told you earlier how time and shell thickness are related.

So, as you are increasing the solidification time; that means, as you are increasing the shell thickness; that means, you are going more inside the cast product, you are dendrites are becoming more coarse. So, please remember higher cooling rate at surface results in finer dendrites spacing, inside the casting you have relatively coarse dendrites because your heat transfer is relatively less there.

So, this is another important you know thing to remember that in a cast product first it is you know you have to near the surface columnar zone and then only at the interior only you have equiaxed zone, but not only that even the columnar dendrites which are forming there not uniform in size. You have relatively fine dendrites at the surface and as you are going inside, you have relatively coarse dendrites it is this is because of heat transfer only. So, the heat transfer at the surface is less oh sorry heat transfer at the surface is more, that is why you have this may higher cooling rate higher heat transfer you have finer dendrites inside heat transfer is decreasing, so you have coarse of dendrites.

Next session I will again talking about some other issues, maybe the effect of chemistry, effect of segregation, and other related issues.

Thank you very much.