Steel Quality Role of Secondary Refining and Continuous Casting

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Module - 06
Lecture - 33
Strength and Toughness of Solid Shell

Now, I will come to certain important you know understanding; some important understanding of the strength and toughness of solid shell. I have mentioned that tuning solidification solid shell has started farming. It has become 100 percent solid at the end of solidification. And then we have only solid, but that toughness and strength at different temperatures we have to be very careful about it.

Now let us see what is happening during solidification here.

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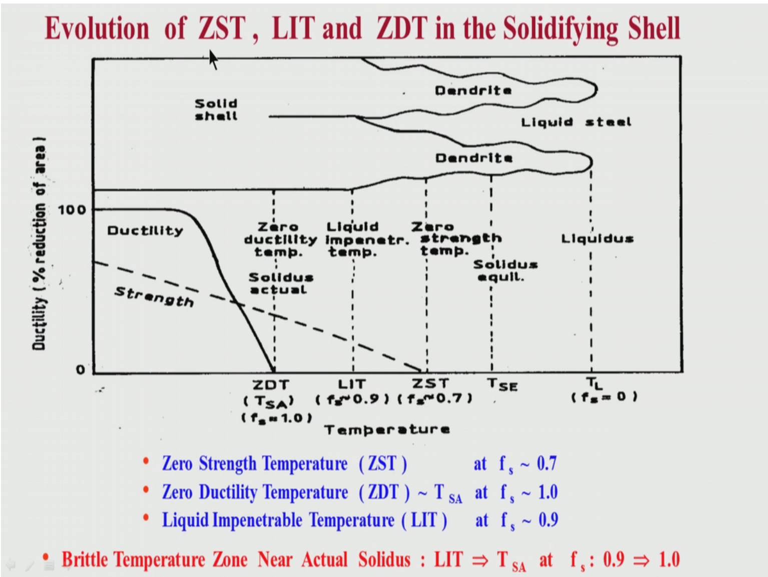

I will give the concept of ZST- I mean zero strength temperature, some people call it NST also that means nil strength temperature. That means, at temperature during casting where the strength is first evolving. The strand initially you have totally liquid and solidification is starting at the meniscus level, as you are going down the continuous caster the solid shell is increasing in thickness, but still there is a liquid. So, it is a strand which is important.

So, in the solidifying shell or the strand what is the temperature when the strength is first evolving? What is the temperature when the ductility of the strand is first evolving? In liquid there is no strand, in liquid there is no ductility. But, at what stage of solidification the strength and ductility are emerging or evolving that is important. Let us try to understand from this figure what is happening.

These are the dendrites which form during solidification. So, what is happening look at here? This is the liquidus temperature; that means solidification is charting at this point at this temperature. So, this is liquidus T L solid fraction f S is equal to 0. So, as you are going down the caster, so the solid shell is increasing slowly. So, we have dendrites, so this area is basically the liquid plus solid zone, because you have dendrite solid you have liquid also. So, at this particular temperature you will find total solidification is complete that mean FS is equal to 1. So, solidification is starting at liquidus temperature, solidification is complete at T SA; that means the actual solidus temperature. So, f S is equal to 1. That means, this is the range of temperature for solidification T L to T SA.

So, now, it has been found that when the solid fraction is around 0.7; that means, you have 70 percent solid 30 percent liquid- in that mushy zone in that area of mushy zone the strand has started developing some strength. When the solid fraction is less than 0.7; some people tell this is 0.7, some people tell this is 0.75 solid fraction when strength is evolving, but what is important to understand is that before solidification is completing the strand has started developing strength.

So, when the solid is 70 percent or 75 percent the strand which has the remaining amount of liquid; that means, maybe 25 percent or 30 percent is liquid. So, that strand has started developing strength. But what is important is that it has no ductility at that particular point of time. Ductility is 0 when the solidus actual solidus temperature is raised. That means, at the point of complete solidification when F S is equal to 1 solid fraction is 1. That means, when solidification has just completed that temperature; what is that temperature it is the actual solidus temperature we will call it T SA.

So, this T SA is more or less equal to the ZDT temperature means 0 ductility temperature nil ductility temperature because only at this temperature the strand starts developing ductility or toughness. So, this is important look at this figure of ductility and this dotted line is the figure of strength in the strand. So, you know when the solid shell is less than

0.7; that means, when the solidification has started and up to say about seventy percent of solidification is over; that means, the solid is seventy percent thirty percent is liquid that is neither strength not ductility in the strand.

When the solid fraction has reached 0.7 or say 0.75 the strand has started developing strength. So, it ZST; that means, the 0 strength temperature on NST the nil strength temperature is more or less the temperature at which the solid fraction its 0.7 or 0.75. So, here strength is less than that there is 0 strength; strength is started developing. So, at this temperature region between ZDT and ZST; that means, between solid fraction of 0.7 to solidification of one what is the situation the strand has strength, but has strength does not have ductility; ductility is starting to develop only at the completion of the solidification and say DT temperature; that means, a T SA temperature actual solidus temperature.

So, in this temperature interval is very interesting to know that this dendrites and the whole strand it has some strength, but it does not have toughness. So, what is the situation like a material feature strain buts no ductility your toughness. So, it is very brittle it is like glass. So, it is very dangerous to handle such material. So, we have to be very careful about this material because there is a possibility of you knows even small strain small force causing crack in this material when the solidification is more than seventy percent, but it is yet to be over. So, this temperature zone is really a method of body, but fortunately for us. Suppose because of the low you know toughness some crack formation takes place and at this surface these dendrites this zone solid zones are relatively why relatively is no toughness at all, but it has some strength.

So, what is happening is if sum due to some strain external strain for internal strain whatever might be the source of the strain because of any force you know which is interacting with this dendrites. So, there is a possibility of crack formation if the crack formation takes place on the surface then what happens? The liquid steel will heal those cracks. So, the possibility of crack continuing sustaining is not there till you know this region. When 2 dendrites are toughing each other; when the 2 dendrites are touching each other, solidification is not yet complete, but liquid is cannot penetrate in this region look at this. So, this normally; this is around 90 percent of solid fraction; that means, when the 90 percent of solidification is complete till that time there is enough liquid you know by the side of the dendrites in the periphery of the dendrites which can heal of the cracks which for conform because of the low toughness of this dendrites.

But in this region; that means, when the solidification is more than 90 percent in this particular region; that means, in the temperature region between solid fraction of 0.9 to 1; that means, near the actual solidus temperature this temperature region is really brittle temperature region because if there is a crack formation in the dendrites the liquid steel cannot penetrate and heal those cracks. So, this temperature is called liquid impenetrable temperature LIT. So, I have talked about three temperatures first it is 0 strength temperature or null strength temperature nil strength temperature ZST or NST which is you know coinciding with solid fraction of say 0.7 or 0.75 during solidification I have talked about ZDT; that means, 0 ductility temperature or nil ductility temperature.

So, this is more or less coinciding with a actual solidus temperature. So, ZDT is coinciding with the TS actual solidus and ZDT more or less are similar. So, this correspond to a solid fraction of 1; that means, when solidification is actual solidification is just complete. Now I am giving another term LIT liquid impenetrable temperature this is basically the temperature corresponding to solid fraction of say about 0.9 and in there is some amount of difference of opinion whether it is 0.9 or 0.85 or say 0.92 or 0.87 nevertheless let us go ahead with this figure that is when solid fraction is around 0.9 then what is happenings the dendrites at touching each other liquid steel cannot penetrate this area.

So, even if there is cracks in this area when the solid fraction is less than 0.9; you know liquid steel can come to the cracks and heal those cracks get in touch with the cracks and heal up those cracks, but in this particular zone; that means, when the solid fraction is more than 0.9. So, beyond 0.9 which is the liquid impenetrable temperature these temperature region is the real brittle temperature region. So, here the toughness of the dendrites is 0 nil, but even if there is crack formation there will be some crack formation because of this low toughness liquid still go and heal those cracks, but in this temperature is in region when again this there is no toughness is here. So, there is a possibility of crack formation, but the liquid still cannot penetrate in this region and hill of those cracks.

So, what is happening here if cracks are forming liquid steel are heeling up. So, even if the dendrites are 0 ductility this temperature region is a relatively safe, but at this temperature region is really unsafe; that means, the temperature between 90 percent solid fraction to hundred percent solid fractions, these particular region here because there is no ductility, but there is strength. So, there if there is a crack formation due to some external strength the liquid steel cannot penetrate and heal up. So, the cracks we will remain. So, this temperature zone is called the brittle temperature zone or region near solidus actual solidus. So, this is please try to remember this is one of the important regions during solidification because this is prone to formation of crack. So, this region towards the end of the solidification is very very prone to formation of solidification crack.

So, we have to be very careful about that. So, I have mentioned here 0 strength temperature ZST corresponds to solid fraction of around 0.70 ductility temperature ZDT corresponds to actual solidus temperature T SA; that means, solid fraction is around point around one; that means, hundred percent solidification; that means, at the end of solidification actual solidification only we are having 0 ductility temperature. So, during solidification the dendrites have no toughness at all they are brittle. So, only after solidification is complete the developing certain ductility and indeed increases as the temperature goes down, but I will discuss later on. That it is not very high at all temperatures what we are showing here is just after solidification of the certain temperature it become it increases to high level and continuous, but as I will show it later on this ductility value again decreases at certain temperature range which we will ca call it brittle temperature regions which is lower to the solidus temperature.

So, what I am telling is around the solidus temperature there is a brittle temperature zone this is the temperature zone during the end of solidification. So, many types of cracks we will be created in those regions because this is a brittle temperature region whatever cracks will form in the dendrites they cannot be healed up by the liquid steel. So, the whole idea is to try to avoid this temperature region; how we will you avoid this? Why cooling relatively faster you do not allow much time for the; you know dendrites or the solid shell to remain in this temperature region that we can avoid this region; you do not allow them to be in this region for large amount of time. So, this is important. So, I have mentioned here does a brittle temperature zone near actual solidus is between solid fraction of 0.9 to 1; that means, the temperature interval between LIT and actual solidus this is the temperature region which is brittled, we have to be careful we will try to avoid this temperature region when solidification is taking place.

Otherwise they will be crack formation which is difficult to hill because you know liquid steel cannot penetrate I think it should be clear to you by this time that though dendrites has started developing strength at around say 0.7 solid fraction. They do not have toughness they start development toughness only after the solidification is complete, but in the temperature region between say solid fraction of 0.9 and 0.7 this region you know there is no toughness, but even if the cracks found the liquid steel sufficiently crystal is they are doing solidification. In this temperature in this you know temperature region between LIT and ZST; that means, between the solid fraction of 0.7 and 0.9. So, even if they are crack formation there will be definitely crack formation, but these cracks are healed up by the liquid steel adjacent liquid steel between the dendrites.

But this is not possible liquid steel cannot penetrate this region and heal up the cracks when LIT there is a liquid impenetrable temperature is reached; that means, when the solid fraction is more than 0.9. So, in the region between solid fraction of 0.9 and 1; even if cracks are forming they cannot healed up by the liquid steel because liquid steel cannot penetrate here liquid steel can penetrate and you know heal up the crack formation in dendrites surfaces the dendrites, but here they cannot because they are touching each other. So, liquid cannot penetrate.

So, these temperature region which is near to the actual solidus temperature is the real brittle temperature zone near actual solidus this is called the high temperature brittle temperature zone because this temperature is relatively high because it is associated with the completion of the solidification. After these, the temperature will only come down because you are cooling it. So, this is the high temperature zone which is brittled high temperature zone near the actual solidus is the brittle temperature zone. So, we have to keep in mind that this is a zone we have to be very careful about.

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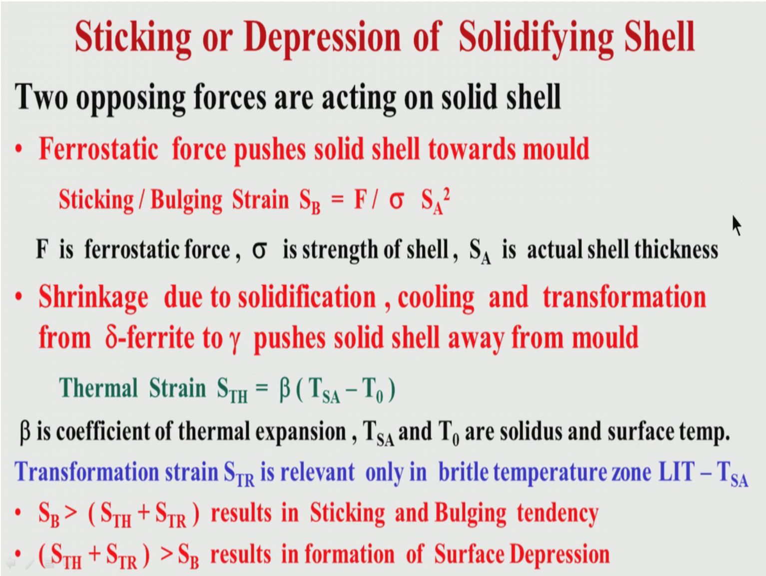

Now, let me try to talk about what is happening in the solid shell what are the different forces which are operating on it; How does it behave because I have told you. It will depend on what are the defined forces or strains acting on it whether they are acting in the same direction or different direction if they are in acting in different direction which force is more predominant.

So, the behavior of the shell solid shell we will depend on that will be dictated by that. So, 2 opposing forces are acting on solid shell what are the opposing forces I have mentioned that first and foremost is the ferrostatic force due to the liquid during solidification there is liquid present in the strand. So, this liquid we will give ferrostatic force we will push the solid shell towards mould when it is within the mould.

So, what is the you know what is the value of that forces strain it depends on the ferrostatic force as such what is the strain on the solid shell which we will try to push it towards the mould or all try to bulge it when it comes out of the mould it is this S B; if you call it the bulging strength S B. It is equal to the ferrostatic force divided by the strength of the shell into the thickness of the actual shell thickness into square I have told you that this shell solid shell strength is very important this value this is the this row is the strength of the shell this will try to resist the force the strain of ferrostatic force.

So, higher this value thicker is the shell more the solid shell can resist. So, this the sticking of the bulging strain we will depend on ferrostatic force is fixed it at a particular level of solidification it goes on increasing as you are going down and down because of the additional what is that called additional force. So, as you go down; the caster ferrostatic force the overall force is increasing, but at a particular level this is fixed f. So, at a particular level the sticking or bulging strain we will depend on strength of the solid shell and the thickness of the solid shell if the strength of the solid shell is low or the thickness is narrow then it cannot withstand the force and say there will be relatively high amount of strain in the solid shell.

So, next; this is one force sticking or bulging another is I have mentioned is the shrinkage. Now this shrinkage is due to what I have mentioned shrinkage can be due to solidification first and foremost whenever there is a solidification there is a shrinkage there may be a cooling because of cooling I have mentioned you that the surface is relatively cooled inside is relatively hot. So, because of this temperature differential that will be a shrinkage because of the cooling and there will be a strain.

So, this cooling and then there is a transformation from delta ferrite to gamma the again there will be a shrinkage there is a density change there is a shrinkage. So, this shrinkage total shrinkage of solidification and cooling and transformation from delta to gamma if you add all this shrinkages then the strain due to the shrinkage it depends on what there are different components I have told you there is due to solidification there is a the saying shrinkage there is a cooling this is a thermal one and there is a transformation.

Now, the thermal one can be found out by using the coefficient of thermal expansion beta and T SA is the actual you know solidus temperature and T 0 is the surface temperature. So, the temperature difference between this and the coefficient of thermal expansion multiplication of that we will indicate what is the strain. So, the thermal strain is because of this on top of this there may be a transformation strain which we call it STR is relevant only in brittle temperature zone I have mentioned in the last transparency that in the brittle temperature zone; that means, this is the brittle temperature zone between LIT and ZDT; that means, between the solid fraction of 0.9 to 1. So, if in this temperature region there is you know transformation from delta to gamma then only this is effective here if you have a transformation it is not effective it will cause crack, but you know liquid steel we will heal it up but if there is a crack formation due to too much of strain here.

So, that you cannot do anything, so, there will be a crack formation. So, whatever strains I am talking about if they form in this region they are really a matter of body or even lower temperature it a matter of body. So, that is why what I am mentioning is the transformation strain relevant in brittle temperature zone between LIT and T SA; that means the solid fraction between 0.9 and 1. So, if let me try to come to very interesting observation here I have talked about 2 strains due to ferrostatic force there is a sticking or bulging strain sticking because when the strain is within mould the ferrostatic force we will push the shell towards the solid shell towards the mould.

But when the strand is coming out of the mould then there is no mould to support. So, what is pushing it is pushing the solid strain and causing bulging in the secondary cooling zone. So, there is a possibility of bulging in within the mould it is sticking beyond the mould lowered as you come down from the mould there is bulging. So, the strain of this it depends on ferrostatic force as you are going down the ferrostatic force is increasing, but as you are going down the solid shell is also increasing thickness. So, what is important is what is the level of f what is the level of sigma that is the strength of the shell here it is important if it is delta the strength is lowered if it is austenite solid I am talking about the solid shell the in the strength of shell whether it is delta or gamma is very important because the strength will depend on that.

Normally authentic solid shell has about 5 times mould strength this please remember this. So, the strength of the shell if it is delta the strength is low if it is gamma strength is more and on top of that what is important is the actual shell thickness I have mention to you that the shell thickness depends on what the shell the actual shell thickness depends on the extent of micro segregation if you are more micro segregation due to phosphorus or due to sulphur then what is there the shell thickness is lowered and the mushy zone is wider. So, if the actual shell thickness is narrow then also there is a possibility of sticking or bulging stain.

So, it is a combination of strength of the shell and the thickness of the shell into square saying this is the square is there. So, this plays a predominant role thickness. So, micro segregation that is why causes is a cause of too much of micro segregation; that means, too much of mushy zone and I have a narrow shell thickness is a cause of high sticking and bulging strain this is one another force just opposite to it this force is trying to push the shell towards the mould and the shrinkage due to solidification cooling and transformation from delta ferrite to gamma this is trying to push the shell away from the mould just see here this force ferrostatic force is pushing the shell solid shell towards the mould the direction of shrinkage whether due to solidification cooling or transformation whatever may be the cause it is time to push the solid shell away from the mould it is shrinking. So, it is going away from the mould towards the liquid and this one ferrostatic force is pushing the solid shell towards the mould that is away from the liquid.

So, these 2 are opposing forces please try to remember so, but which force is mould which strain is mould we will determine whether there will be sticking or bulging or they will be shrinkage. So, this is very important concept try to understand the certain grids we call it they are prone to sticking or bulging and certain grids of steel we call them that they are prone to shrinkage this is because of this consideration if the you know ferrostatic force is such that the sticking or bulging strain. So, it depends on what ferrostatic force the strength of the shell in the thickness of the shell. So, these we will determine what is the bulging or sticking strain. So, if sticking strain is more than the shrinkage strain shrinkage strain is a here 2 component one is terminal another is transformation.

So, 2 together is important. So, if SB; that means, the bulging strain is more than the shrinkage strain due to thermal shrinkage as well as confirmation shrinkage then say this strain is more; that means, there will be sticking inside the mould and bulging below the mould and if the reverse happens; that means, if this strain shrinkage strain due to you know thermal or you know transformation strain if this addition of those strains due to shrinkage is more than the you know strain caused by the ferrostatic force then what is the consequence this will result in formation of surface depression.

So, the surface depression is characteristic of certain steel grids and sticking on bulging are similarly characteristic of certain other grids of steel. So, grids of steel why it is important because I have told you whether delta gamma will form depends on the chemistry how much will the shell thickness depends on the chemistry and depends on the micro segregation. So, these are very important. So, what is the thermal strain this is again depends on the chemistry to certain extent what is the; you know delta to gamma transformation when does it take place whether at all it will take place again depends on the chemistry. So, many factors are contributing to the different levels of sticking or bulging strain or the strain from the shrinkage. So, the relative values of these 2 strains we will determine what are the sticking or depression tendency.

Thank you very much.