Steel Quality Role of Secondary Refining and Continuous Casting
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Module – 07
Lecture – 35
Sticking vis-a-vis Depression Behaviour

In the last session I talked about the zero strain temperature, the zero ductility temperature and the liquid in penetration temperature. These are basically important parameters which we have to keep in mind while considering what is the you know strength or ductility of the solidifying shell; like what I mentioned was that when solidification is taking place.

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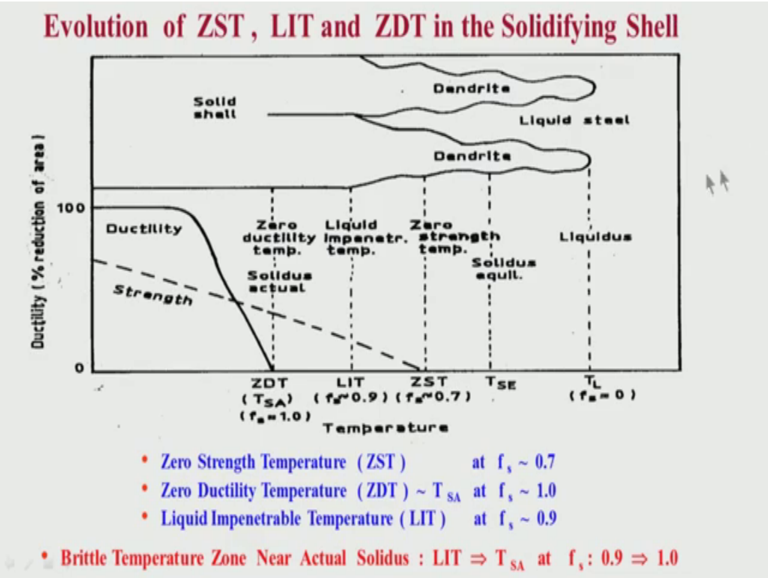

So, these are the dendrites which are forming and the you know mushy zone you have you have both dendrites as well as you know liquid steel and this is of course, the total solid shell. That means, this temperature corresponds to the liquidus temperature TL. So, here the solid fraction is 0 and you are you have completed the solid fraction say at this location; that means, I had TSA that means, the actual solidus temperature corresponds to here and the solid fraction is one; that means, 100 percent solid, this is 0 percent solid beyond that is in liquid steel and beyond this we have solid shell.

So, the question is at what temperature the strength of the you know solidifying shells you know strand, what temperature does it develop strength that is what is important. So, I have mentioned that at around solid fraction of 0.7 or 0.75, the strand is developing some strength when the solid fraction is less than that; that means, from solid fraction of 0 to say 0.7 or 0.75. So, dendrites have formed, but the liquid steel also is quite substantial amount present. So, the strand the does not have strength. So, the strength is developing only at a temperature which we call it zero strength temperature, which corresponds to solid fraction of 0.7. So, 70 percent solid is there, 30 percent is liquid the strand is starting to develop strength and this is the strength this dotted line.

So, you see the strength has started developing you know above this temperature when the solid fraction is less than 0.7; there is no strength in the strand at all. So, we have trying to we have trying to tell you that the strand is developing strength at a solid fraction of 0.7 and then it is increasing. As we are coming down so, when we are at the actual solidus temperature; that means, the solid fraction is one what do you get you get some strength, but look at the ductility figure ductility of the strand ductility you know beyond you know ductility in the range of say this range you; that means, when the strand has developed strand, but you do not find any ductility. So, it has a zero ductility in this region.

So, in the temperature range between correspond rather corresponding to solid fraction of 0.7 and 1; that means, when the solid fraction is 70 percent to100 percent, in this temperature region the strand does not have any ductility, but it has some strength strength has started at around 0.7 solid fraction at you know this temperature that which has the temperature 'corresponding to solid fraction of one that in men means when the solidification is just completed at this region you know strain ductility has just started to developed. So, in this particular region corresponding to solid fraction of 0.721 the strand has strength, but it does not have ductility. So, what is the implication of that? The implication is this area is very brittle it is the like glass it has strength, but it does not have any ductility; that means, whenever there will be some strain or stress or force which is imp getting impinged on this solidifying strand or shell, what is going to happen there will be crack formation because there is no toughness though ductility and around this temperature.

So, they will be crack formation, but fortunately since liquid steel is available between say 0.72 and 0.9. So, whenever there is a crack formation this liquid steel will be available to heal up the cracks. So, crack formation will be their because it is brittle because you know strength is there, but there is no toughness or ductility. So, what about strain will be impinged getting impinged on the shell it will cause crack formation. So, crack formation will be there, but between say 0.7 to 0.9 solid fraction since liquid steel is available, liquid steel will move and heal up those cracks because liquid steel is available at the surface regions of the dendrites inter dendrite (Refer Time: 05:40) the region in there is sufficient liquid steel, but what happens say along this when solid fraction is say 0.9. So, the dendrites are touching each other that means, if there is a crack formation in this area liquid steel cannot penetrate.

So, that is why this is called liquid impenetrable temperature; that means, at this temperature which corresponds to 90 percent of the solid fraction, what is happening liquid steel cannot penetrate and if there is a crack formation that crack is going to stay. So, it is a problem for the quality of the cast. Why because cracks whatever is forming because of the brittleness the remaining in the cast products. So, there is in a no chance to heal it. So, therefore, this particular temperature range; that means, corresponding to the solid fraction of 0.9 to 1 that means, around the actual solidus temperature this area is called the high temperature brittle range or brittle temperature zone because as you are coming down in temperature during solidification, there is you know no ductility here no ductility beyond this temperature this is called the 0 ductility temperature, and 0 strain temperature is around you know solid fraction of 0.7 we call it ZST zero ductility temperature more or less (Refer Time: 07:16) which is the actual solidus temperature; that means, at a solid fraction of one; that means, when a solid fraction solid deification is just complete then only the strands starts developing toughness or ductility.

So, this temperature region; that means, the temperature region near the you know solidus temperature is really the brittle temperature zone because here if the cracks are forming they cannot heal because the liquid steel is not there. So, this is the real zone of or effective zone of brittle temperature, where brittleness where you know if there is a crack formation those will remain. So, we have to be very careful about this temperature region which is the brittle temperature region at high temperature. So, this corres this is called the zero ductility temperature from here only ductility stress improving; that means, even slightly below this temperature ductility is also quite low.

So, there is a chance of crack formation around this temperature region; that means, around the brittle around the actual solidus temperature the brittle zone exists. So, we have to be very care full while the strand is getting cooled you know solidification this temperature region, we have to be very careful about. So, brittle temperature zone near actual solidus; that means, between LIT and TSA that means, in the you know solid fraction region of 0.9 to 1 it is 0 ductility, and beyond this ductility slowly increasing. So, even slightly lower than this temperature ductility is also quite low. So, this temperature region is called the brittle temperature zone near actual solidus.

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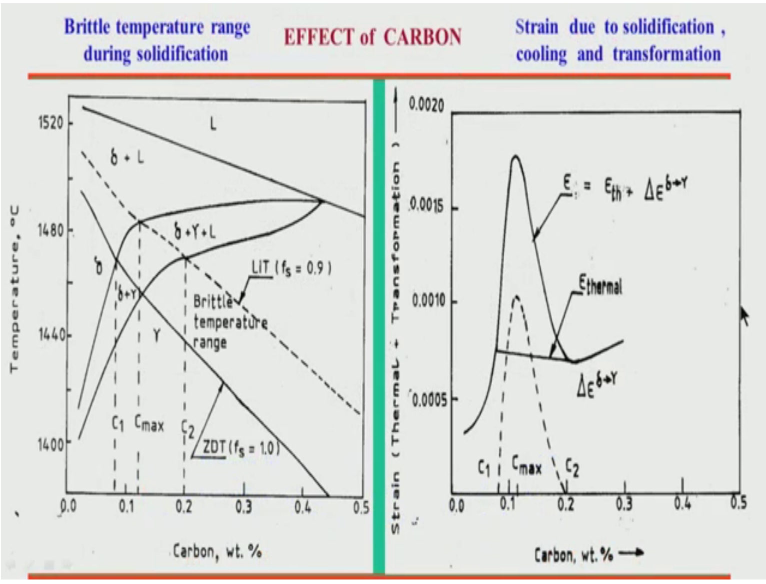

So, we have to be very careful about this particular temperature. Then I have talked about how you know the carbon is affecting this brittle temperature region during solidification I have talked about the brittle temperature region, which is near the actual solidus region between solid fraction of nine and solid fraction of one.

So, let us see with carbon how does it change, how does it vary with carbon because definitely it will change with carbon because you know why because the actual solidus is also changing because of the carbon content, because of the mode of solidification. So, this brittle temperature region also is changing with carbon, now let us see what is how does it change. So, for a carbon content which is less than say C 1, C 1 a particular you know carbon content or you less than that this what is happening how is a solidification take it has liquid then it comes to delta plus liquid; that means, delta solidification and then solidification is complete there is no you know sign of austenite till then. So, solid is totally delta after solidification, after certain temperature only when the temperature is coming down then only gamma is farming.

So, the solidification is totally through delta and whenever total solidification is complete we have 100 percent delta and when the temperature is coming down after certain temperature interval only you will get delta to gamma transformation in solid state, but in liquid state; that means, during solidification that is no gamma no austenite. So, beyond C 1 when a you when we are increasing carbon content above C 1 what is happening look at here. Solidification increase initially again though delta amount then this is the temperature when gamma transformation is starting delta to gamma, you know because of the eutectic temperature because of the eutectic reaction. So, what is happening is delta to gamma is taking place in the brittle temperature region. What is the brittle temperature region this is dotted line and this line; that means, at point between 90 percent solid fraction and 100 percent solid fraction.

So, solidification is getting complete at this particular temperature. So, here within this temperature range above C 1 this transformation from delta to gamma is taking place. So, delta to gamma is taking place means I have told you earlier what is the implication there is a shrinkage from the delta to gamma transformation, and shrinkage means there will be a strain there will be stress and the solid fraction solid now whatever solid you have. So, what is going to happen this stress or strain is adding to the solidification strain or stress. So, at carbon concentration above C 1 we are having this transformation delta to gamma in this brittle temperature region.

Now, what happens at C max this particular chemistry is around slightly above 0.1 around 0.1 only. The total delta to gamma transformation is taking place in this brittle temperature region here some of the transformation is taking place in brittle temperature region. Here the maximum transformation for the delta to gamma is taking place in the brittle temperature region is it clear this is the this line is basically delta to gamma transformation line start and this is complete. So, the start it is taking place when C 1 is increasing. So, as we are increasing carbon concentration from C 1 and going to C max more and more of delta to gamma transformation is taking place in the brittle temperature region.

So, at C max maximum transformation from delta to gamma is taking place in the brittle temperature this is very important to note. Now when you are going above C max let us see what is happening. C max I have told you maximum delta to gamma is taking place within this temperature region, this is the delta to gamma transformation complete and this is the delta to gamma transformation start. So, as you are increasing carbon concentration above C max more than C max when you are going. So, again the transformation has started above the brittle temperature region and some of the transformation you see is happening in the brittle temperature region. Now look at this figure C 2 what is happening here at C 2 the transformation delta to gamma he has is taking place above this brittle temperature region.

The end of the brittle temperature region is coinciding with the end of the rather delta to gamma transformation is coinciding with the start of the brittle temperature region here so; that means, between C 1 and C 2 delta to gamma transformation during solidification is taking place in the brittle temperature it is starting at C 1 it is completing C 2, and the maximum of transformation from delta to gamma is taking place at C max which is this brittle temperature region. Above C 2 what is happening with the carbon concentration is more than C 2 the delta to gamma transformation is taking place during solidification, but above the brittle temperature it is taking place here, when the you know the concent rather the amount of solid is say about 50 percent, 60 percent, 70 percent it is taking place.

So, it is above it is taking place above the brittle temperature region it is between solid fraction of 0.9 to 1. Again I am mentioning this temperature region between solid fraction of 0.9 and 1 the temperature between liquid impenetrable temperature LIT and ZDT 0 ductility temperature which is corresponding to the completion of solidification temperature this is the actual solidus temperature. So, this is the brittle temperature region. So, this carbon region from C 1 to C 2 is the carbon concentration we have to be careful about, because why what is happening the any steel which is having carbon concentration within this region delta to gamma transformation during solidification is taking place within the brittle temperature region. So, this is a very critical concentration region we have to be careful about because there is scope for crack formation in this for this concentration region and this concentration incidentally is around the 0.1 percent carbon, its start slightly lower than 0.1 and continuous up to say about may be 0.2.

So, this is the carbon concentration at which point at which region rather of concentration the delta to gamma transformation is taking place within the brittle temperature region. So, what is the implication, you will find the implication here, here strain has been calculated and plotted for carbon concentration. In this diagram we are you know plotted the brittle temperature range during solidification, how is it changing with carbon concentration. So, now, we are actually plotting the strain. So, the I have told you the shrinkage strain is a combination of two or three things one is the thermal strain thermal basically consists of two components one is due to solidification another is due to change in temperature. When cooling is taking place during solidification itself for less than that you know lower than that. So, then this epsilon; that means, the strain due to thermal consideration and this is the strain due to delta to gamma transformation.

Now, see what is happening, this is the I have told you the between C 1 and C 2 the delta to gamma transformation takes place in the brittle temperature region, that is why you will find the strain beyond low lower than C 1 it is almost 0 above C 2 again it is almost 0 because it is taking place either below this brittle region temperature region or above the brittle temperature region. So, the strain is maximum at C max as I have told you why it is maximum because the all the formation of delta to gamma is taking place at a concentration of C max in the brittle temperature region. So, that is why at C max this transformation strain is maximum at C 1 then it is coming down and less than C 1 it is 0 and again also it is coming down from C max to C 2 and above C 2 again it is 0 and this one is the thermal strain. Thermal strain initially you know at delta solidification it is very low slightly increasing and then above you know 0.2 it is again increasing because that temperature interval increases because of you know difference in the or temperature difference between liquidus and solid actual solidus increases because of two factors first there is a chemistry effect because of carbon and also because of micro segregation.

So, this will increase beyond say 0.2 which is going on increasing, but what is important to note that between C 1 and C 2 the total strain is quite high, here beyond 0.2 thermal this thermal strain is increasing, but transformation strain is not there, below C 1 thermal strain is also low and transformation strain is 0. So, less than 0.1 less than you know C max C 1 the strain is very low. So, the probability of you know formation of crack in this temperature region along this brittle temperature region is almost nil, but between C 1 and C 2 the probability of crack formation is high and it is maximum at C max. So, that is why we call that peritectic chemistry; that means, the chemistry or the carbon at the start of the peritectic reaction this is the start of the peritectic reaction when delta to gamma transformation is taking place through peritectic reaction during solidification.

So, from C 1 to C 2 is the zone of concern chemistry area of concern because here the strain is quite high because of delta to gamma transformation. So, in this brittle temperature region there is a possibility of crack formation. Now I will be talking about based on whatever understanding we have developed on the strength and ductility of the you know strand solidifying strand.

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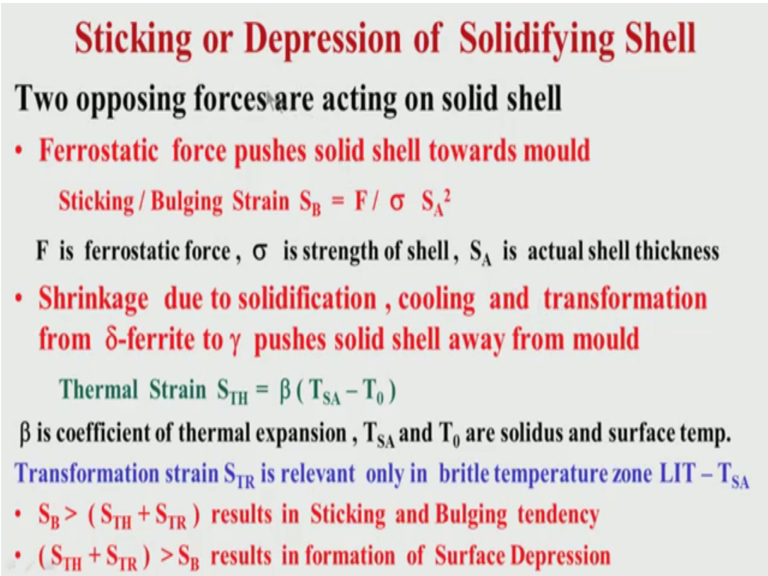

Now, let us try to understand how this solid shell will behave for different concentration of carbon. That means, when initially the shell is forming what are the forces on it, there are two opposing forces acting on the solid shell I have told you that depending on the whatever I will be now talking about there are two opposing forces one is the ferrostatic force, ferrostatic force is basically due to the liquid steel which is existing during solidification. This ferrostatic force during solidification pushes the solid shell towards mould. I have told you earlier this is pushing the solid shell towards the mould and where you are coming below the mould it is causing sort of bulging; that means, it is pushing the solid shell away from the liquid steel.

So, this ferrostatic force pushes the solid shell towards mould or away from the liquid steel. So, what is the sticking or bulging strain you can calculate this, it depends on the ferrostatic force it depends on the strength of the shell sigma, and it depends on the actual shell thickness SA square of that. So, shell thickness is very important here. So, higher is the ferrostatic force; that means, as you are going to more and more of solidification; that means, we are going down the ferrostatic force is increasing. So, towards the end of solidification ferrostatic force will increase. So, they will be more of this strain and also it depends on it will depend on what it is it will depend on the sigma strength of the shell. If the strength of the shell is more this strain can be less that means, what is resisting the ferrostatic strain or force it is basically the strength of the shell and the solid shell thickness.

So, solid shell thickness if it is thick it is wise because it is the square root of that. So, it can resist it appreciably. So, the strength of the shell and the thickness of the shell these two are important parameters through resist this sticking or bulging strain. Why it is called sticking the solid shell we will try to come towards the mould. So, is a tendency for the mould to stick tendency for the shell to stick to the mould wall. So, here the role of you know the thickness of the cast under the casing we have power or you know the mould, powder of the mould, slag which is found from the powder that is very important. So, that has two resist this you know that is important, otherwise they shell we will try to stick to the mold. So, this is one force another is the shrinkage which is the opposing force, you know this force is acting away from the liquid towards the mould, but the shrinkage in which direction does it act, it will act towards the liquid steel and away from the mould opposite to the ferrostatic force.

So, now shrinkage it due to what due to solidification due to cooling and due to transformation from delta ferrite to gamma. So, solidification shrinkage cooling shrinkage and thermal shrinkage, and transformation shrinkage, all these act together we will cause the shell to move away from the wall and towards the away from the mould wall and towards the liquid steel. So, here ferrostatic force is pushing the shell towards the mould away from the liquid steel and here shrinkage is pushing the shell away from the mould towards the liquid.

So, these two forces are opposing this two strains are opposing each other. So, this can be calculated thermal strain can be calculated basically you know coefficient of thermal expansion and the temperature difference between the solidus and the you know surface temperature, and the yeah and the solidification strain also can be calculated how much solidification, temperature difference is there all these six can be calculate. And last you know transference I have told that thermal this delta to gamma transformation strain also can be calculated from the density difference between delta and gamma, we can calculate the strain there you know the shrinkage due to delta to gamma transformation.

Though this strain also can be calculated. So, finally, which one is more? The sticking or the bulging strain is more compared to the thermal and you know transformation strain. If this is so, then there will be sticking or bulging tendency if reverse is two; that means, the strain due to thermal and transformation is more than the bulging strain then the consequence will be formation of surface depression. So, it is clear now that for certain chemistry they will be sticking or bulging tendency or we will come to it now and for certain chemistry they will be depression formation. That is why we call it sticking or depression of solidifying shell there will be either sticking or depression depending on which strain is more whether bulging strain is more or the shrinkage strain is more depending on that if the bulging strain is more sticking strain in more will have sticking tendency, but we have shrinkage if the shrinkage strain is more compared to this we have depression tendency of the solidifying shell.

So, this to behavior sticking or depression it is intrinsic to the steel chemistry. Steel chemistry we will determine how the solidification takes place what are the solidification constituent delta to whether it is delta or gamma, whether you know the chemistry again we will dictate how much is the micro segregation, this we will dictate what is the actual solidus, this we will dictate how take we will be the solid shell, and what is the thickness of the mushy zone. So, all this we will determine what is the relative sticking or depression behavior for any particular chemistry.