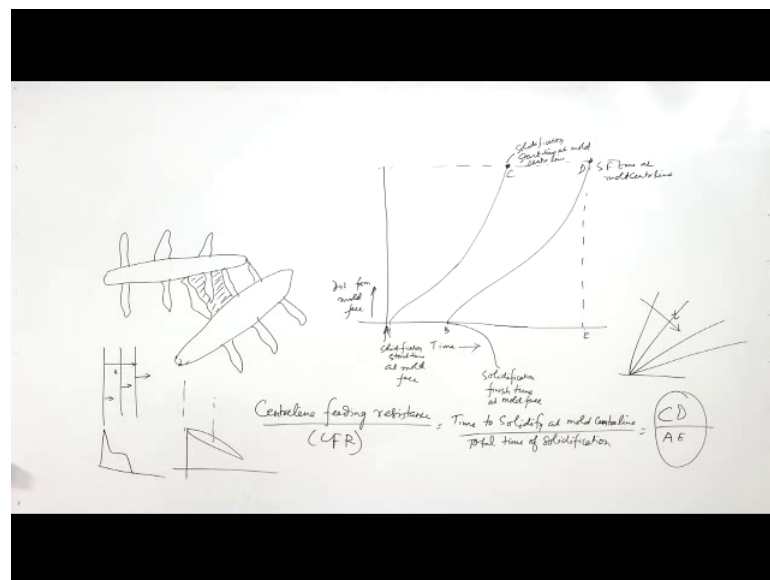


Theory of Production Processes
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Lecture - 04
Factors Affecting Solidification Process

Welcome to the lecture on factors affecting solidification process. So, in the last lecture, we discussed about the constitutional super cooling and we saw that how there is the dendritic type structure formed in case of alloys. In the case of pure metals you have formation of equiaxed grains, then you have columnar growth of grain, and then that is going till the centre point of centres line section of the casting, and in the case of alloys the thing is that this growth takes place in a way that you have the dendritic arms a tree like structure. Now this tree like structure as we discussed, they are basically harmful in the sense that basically in between the arms, there is probability, there is chance that there will be trapment of liquid metals.

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So, suppose you have many you know trapments, you have this way, you have dendritic arms you will have one dendritic arms like this. So, suppose you have here, you have here.

So, in that what you see if suppose such is the dendritic arms in those cases, and you this is just a case which we are discussing. So, what we see is that this liquid which is trapped

suppose in this zone, this zone gets is very much prone to have the shrinkage defect because it is and also you have other from all the sides, if such are the zones which are trapped which does not have the connection with the active feed channel, because in the case of casting what happens that as it gets solidified and since the density of solid is more than that of liquid.

So, there will be shrinkage of the liquid metal, and that void which is created that is being compensated by one extra reservoir that is known as riser or you will have any extra way or path by which this extra metal should come and fill that point where the void is created. The so, what happens there a chance that here there are source of defects, you will have the chances of entrapment of the liquid metal in isolation and that may lead to shrinkage.

So, we should try to; now we cannot avoid it because this is the trait of the alloy which has the freezing range, the it has to go maybe that the dendritic arm spacings can be controlled or if you can control the magnumity of such dendritic formation or extent of this kind of structure, but this cannot be avoided because this happens because of the concentration gradient, and that is a part of such alloys or a trait of such alloys. Now what we see that in the case of metals we see that this is advancing uniformly, this is advancing front, this is going on so uniformly. Whereas, in the case of alloys because you have the cooling curve like this, this is in the case of metals you have the cooling curve like this. In the case of alloys your cooling curve is like this. Now what happens at any instance of time, at any point of time wherever the solidification starts the solidification has also to end and since it is not done at a constant temperature so, solidification to finish at a point you need the time that whenever that when it will be finished at that particular point.

So, what happens in the case of alloys, you have basically it can be better understood by a freeze wave mechanism. So, what happens when the liquid metal is poured into the mold? Now the thing is that you will have this as the centre line of the casting, and this is the distance from the mold face. So, this is distance from mold face and this is time. So, what happens when you pour the liquid metal, the liquid metal which is at the mold face it will try to immediately solidify or it will take very less time to for solidification to start and but the solidification is starting at this time and it will take some time to finish.

So, it will take suppose this time to finish. So, this is the solidification start time at mold face, and at the mold face the solidification gets completed here. So, this is solidification finish time at mold face. Suppose you have taken the sand mold, in that case what you see is, but what you can get it. There has been experiments; where you have the mold, and you have the liquid metal, and at every point you give the thermocouple, and that will give you the temperature readings and it was seen that such is the such are the time at which it was seen that it starts here and it gets finished here. Whereas, in the centreline at this point the solidification was over, and further you when the different at different points the temperature are recorded and seen that when the solidification gets completed, the solidification complete line goes like suppose this.

So, this is the solidification start time. So, this point you see that here at the wall quickly the solidification is finished whereas, in the centre this is the solidification start time. Solidification start time at mold centre line and this is the solidification finish time at mold centre line. So, basically what happens it goes in a wavy manner, it starts at this place and then slowly it moves, and it with this start time. So, start that the mold face will start very immediately because it will experience the largest under cooling, whenever it touches the whole face and then in this time it will finish, it will start at the mold centre line whereas, here it will start at the it will finish at the mold face at this time, and then it will reach at this point.

So, that ultimately your whole casting although casting solidification starts at this time, but it finishes whole together altogether at this point. Now what we saw that in the case of alloys, initially what we see is you will have the columnar ghendendritic dendritic structure. Initially seems the under cooling is maximum, the heat extraction rate is maximum, the temperature gradient line is the steepest one in that case you will have the start of solidification here quickly, and you will have the equiaxed grain here very fine equiaxed grains, then you will have columnar grains growth taking place.

Now, in that case greater growth is taking place in this fashion slowly not here not near the wall maybe yeah as we go as you move further into the liquid metal towards the mold centre line, and you will have the columnar dendritic grains. Now in the middle portion since the because the temperature differential becomes low, the since because of the release of the latent heat and that release of latent heat and it goes towards the central portion so that differential will be even lower and lower. So, that will be equalized in the

temperature and your basically heat extraction rate or the thermal gradient line becomes even smaller and smaller.

So, earlier the gradient line which was like this, it went can go like this and this. So, as the time progresses the gradient line becomes less and less steeper. So, once it becomes more and more steeper, I mean in this cases you have the chances of plane front solidification whereas, when your gradient line thermal gradient line is slowly getting less and less steeper towards the central zone, in those cases there are chances of equiaxed dendritic kind of structure.

So, now what we see here is, that it starts here and it finishes here. So, there is a parameter which is defined this parameter is centre line feeding resistance. Now what we see why we call it as because that when we move towards the centre. The centre part will be more prone to have all these kind of defects. So, basically when you have large freezing ranges; as the freezing range becomes more and more in the case of alloys the more difficult situation is, those situation where you have to feed it properly. So, as you go towards the centre then there will be more and more resistant for feeding, it will be very difficult to get a very clean structure defect free structure, because more and more chances of having shrinkage kind of defects getting the liquid entrap in between the arms of the dendritic structure becomes more and more.

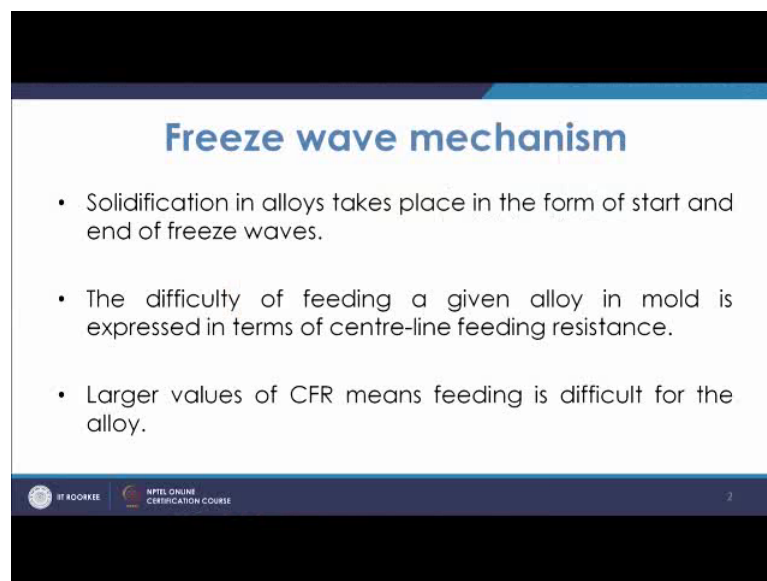
So, what we see is there is a parameter, which is defined that is known as centre line feeding resistance. So, centre line feeding resistance tells I mean it basically the term itself indicates that there is a resistance which is trying to be fed at this mold centre line or the casting centre. Now this resistance is will this feeding CFR. So, that is it is also known as CFR. So, CFR is defined as the time to solidify at mold centre line divided by total time of solidification.

Now, what happens in this case as you see your time to. So, this is basically your total time of solidification. So, if you take this point as A, and this is B this is C and this is D and this is E. So, assuming that normally the soildification will start I mean at the face as soon as it is poured into the mold, in that case you can take this as the origin one and what you see is the time to solidify at mold centre line will be CD. So, it will be CD and divided by AE.

So, basically this time divided by the whole solidification time, this ratio is known as the centre line feeding resistance and this is very important parameter because if there is more and more width to this region that basically increases the probability of having problem of feeding. So, basically the alloy is considered as difficult to be fed if the CFR value is more. So, if it is more than 65 or 70 percent, it is the alloy is completely difficult to be fed there are chances that there will have lot of defects especially towards the centre line of the casting whereas, if it is smaller value like 30 to 35 percent, its quite reasonable quite 35-40 percent, 50 percent, even is acceptable.

So, what is seen is that this CFR value should be a smaller one so, that you can say that it is easy to fit. So, what we see that certification in case of alloys take place in the form of start and end of freeze waves, these are known as the freeze waves the start of the freeze wave and this is the end of end of the freeze wave. So, this is known as the freezing wave mechanism to stud to study the solidification process in case of alloys.

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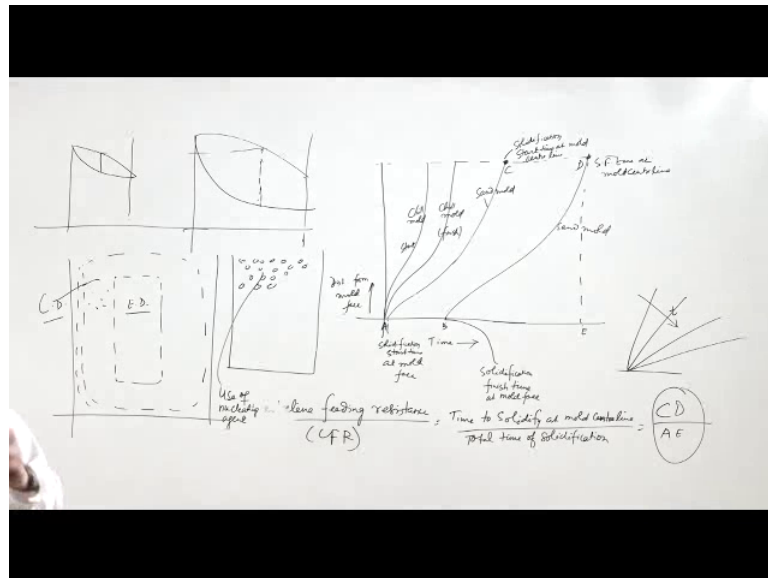
The slide is titled "Freeze wave mechanism" in blue text. It contains three bullet points: "Solidification in alloys takes place in the form of start and end of freeze waves.", "The difficulty of feeding a given alloy in mold is expressed in terms of centre-line feeding resistance.", and "Larger values of CFR means feeding is difficult for the alloy." At the bottom, there are logos for IIT ROORKEE and NPTEL ONLINE CERTIFICATION COURSE, and a small number "2" in the bottom right corner.

The difficulty of feeding a given alloy in mold is expressed in terms of centre line feeding resistance and larger the value of CFR means the alloy is more and more difficult to be fed. Now what is why it is important to study this? So, you will have different variables which affect this started end of the freeze wave.

So, the different variables are you have solidification range of the alloy. So, if the solidification range of the alloy is more, in that case the separation will be increased. As

you as discussed that if the alloy has large solidification range, there will be larger chances of the problem of feeding it, if because if there is large. So, as we see we have seen that in case of alloys.

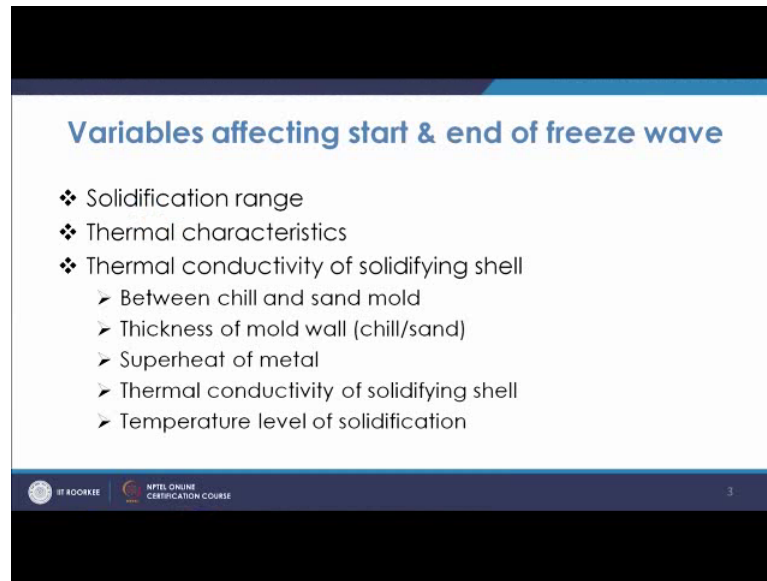
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You will you may have this kind of phase diagram or you may have suppose this kind of phase diagram.

Now, in this case the solidification starts may be at the same temperature, but then it will in this case it has it can be said that as it soon as it reaches here, the solidification is complete whereas, it has to traverse long distance. After lot of time it takes to finish and the situation becomes more and more severe towards the central part of the casting central line of the casting. So, if the solidification range of the alloy is more, in that case the CFR values will be more and that basically will increase this width the gap, I mean the time required to solidify at the centre line. And if it is more in that case the CFR value will be more, and then the there will be chances of defects and then the alloy it may be said that it will be difficult to be fed.

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Variables affecting start & end of freeze wave

- ❖ Solidification range
- ❖ Thermal characteristics
- ❖ Thermal conductivity of solidifying shell
 - Between chill and sand mold
 - Thickness of mold wall (chill/sand)
 - Superheat of metal
 - Thermal conductivity of solidifying shell
 - Temperature level of solidification

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Thermal characteristics. So, that is that I mean it may be between. So, first is thermal conductivity of solidifying cell. Now in this case the first point is that how your thermal conductivity of the solidifying cell will change. So, among a thermal characteristics, the first is the thermal conductivity of solidifying cell. Now if the thermal conductivity of the solidifying cell is more the general effect is that if the thermal conductivity is more it will try to have the equal temperature inside.

So, in that case it will basically increase the separation. So, being this thermal conductivity if it is more, that will lead to the increase of separation and the CFR value will be likely to be more. Next point is between chill and the sand mold. Now the thing is that when you have the one mold is made of sand and another mold is made of metal what happens in that case. So, when you have the chill mold in the same case, if you have the chill mold the pattern may move like this.

Now, this is basically for sand mold start and finish, and this will be for chill mold; chill start and chill mold finish. So, if you have two mold one is made of sand, another is made of metal. In the case of chill mold since the heat extraction rate is quite fast in that case there is less time for the solidification to be complete. It starts quickly at the mold wall and even that because of the large heat extraction rate. There will be a gradient developed and separation or width in between the lines will be smaller.

So, this is how it shows the effect of the molding material, whether it is chill mold or a sand mold this freeze wave lines will be changing next is thickness of the mold wall. So, thickness of mold wall basically that also is important in the sense that increasing the thickness of a chill mold wall will increase the solidification rates and so, beyond that point basically no additional effect is realized.

So, up to a certain point if you increase the thickness, in that case for the chill mold wall it will increase the heat transfer it and after that there is no effect. Similarly in the case of sand mold; in that case heat removal rates are increased by decreasing the mold thickness. In the case of chill mold if you have the larger thickness values, the amount of heat which is extracted that will be more, but not beyond certain point similarly in the case of sand mold if you decrease then it then basically the heat extraction will be more. So, it will be increased by decrease in the mold thickness below a certain thickness.

So, above this thickness there is little effect, then you have next point is superheat of metal. So, it has the effect of. So, once you have the more superheat, it will try to push the lines towards the right. So, in that case you will have the chances of having more CFR. So, that it moves these lines towards right in both either chill mode or in the sand mold. Temperature level of solidification; so, how this temperature level of solidification basically changes. So, a low temperature level of solidification that will basically reduce the temperature gradient and then that will increase the separation between the lines.

So, if you have the higher temperature level of solidification, if the solidification is occurring at high temperature in that case there is more chance of having large temperature gradient, and if there is large temperature gradient its chance of larger heat transfer more, steep temperature gradient line and in that case there will be a smaller gap. So, in that case the low level of low temperature level of solidification, it will be increasing the gap. So, it will be not that much favourable.

Now, what happens as we discussed that these commercial alloys, what we discussed that in case of commercial alloys what happens. If you take the commercial alloys normally you will have the columnar dendritic grains in the bulk portion near the wall; near the wall you have initially you have solidification start at the walls and then you will have the formation of dendritic grains columnar dendritic grains near the walls it will start growing and then in the central portion you will have you will have the formation of

equiaxed dendritic. So, you will have in this zone, in this zone you have columnar dendritic structure and here you have equiaxed dendritic structures.

So, because as we discussed that the temperature differential will be low enough to promote the random nucleation, so in that case the structure becomes equiaxed dendritic. Now the thing is that many a times these we try, why it happens as we see in these cases that, because of the thermal conditions because of the temperature conditions, it so happens that the nucleation is remove I mean reduced the chances of a nucleation is reduced, because the under cooling is I mean the superheat is gone, the temperature does not come down because it is getting equalized because of the release of the latent heat. So, there is another practice which is followed in the case of industries, where you promote the formation of more nucleus.

So, one of the method to promote the formation of these equiaxed grains or having more nucleation sites, will be with the use of inoculating agents nucleating agents are added into the melt. So, these nucleating agents are inoculating agents, they work as the independent nucleation centres. So, if you use the nucleating agents will be whole domain will be equiaxed structure. So, basically this will be because of the use of nucleating agent. In practice in many cases in the industries, we apply certain you know alloying element which act as the nucleating agents to have very fine grained structure.

So, you have many ferrous materials I mean variety of steel is there or we have duplex steel. So, which has basically the use of these nucleating agents and these nucleating agents are used to refine the structure to make the grains refined. Now the thing is that we try to have these equiaxed type of structures, and because the columnar dendritic structures are not that we desirable because you have the dendritic arms, and this as we discussed that you have the chances of liquid metal getting entrapped in between the dendritic arms and then that will be source of the casting defects.

So, what has been seen that now the anyway in the case of commercial alloys, this is the normal typical structure where you will have the columnar dendritic grains, and near the surface and then you will have equiaxed dendritic grains near the centre of the casting. Now the ratio in which this equiaxed to columnar grains that will vary, it will vary upon these factors like inversely proportional to the effective superheat. Means if the superheat is more in that case the ratio will be less. It is so, because if the superheat is more the

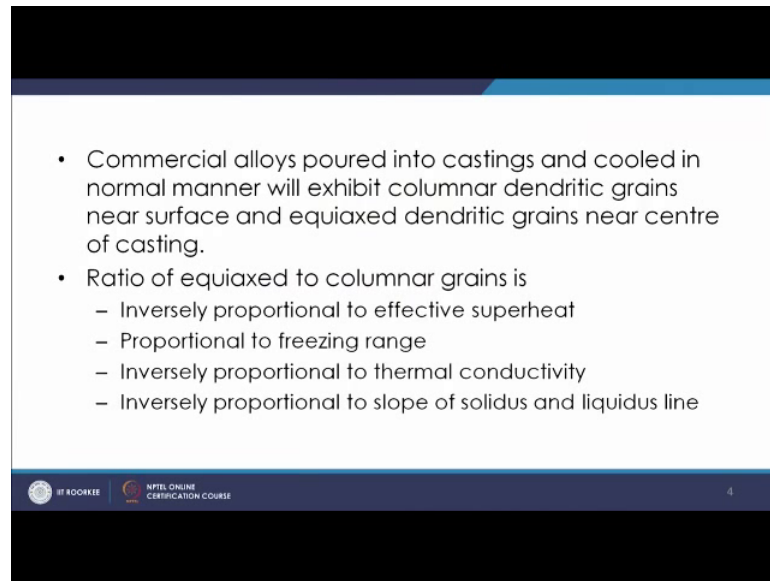
more will be to I mean contributed towards this region to in the region near the wall, you have these dendritic structure, you will have columnar dendritic structure.

So, having more superheat because of larger temperature you will have growth of these dendritic columnar dendritic structures more predominant, and in that case this portion will be more and that will be making the equiaxed structure in the centre to less. So, that is why it is inversely proportional to the effective superheat. So, superheat being more you will have the ratio of equiaxed to columnar grains will be lesser. Similarly it will be proportional to the freezing range. If the freezing range is more the equiaxed grains proportion will be more; because as you discussed when the freezing range is more towards the centre it will take more time to solidify and in that case what happens in very less time what happens the temperature gradient line becomes so, that you will have the random nucleation possible because of the thermal conditions.

So, when the freezing range will be more, in that case this portion this portion will be less you will have the start in the start you will have formation of the columnar dendritic structure. But slowly that the line the temperature gradient line which we see here that basically slowly goes on getting less and less steeper. So, that basically leads to the promotion of the formation of equiaxed grain at early time. So, if the freezing range is more in that case the EQ ratio of equiaxed to columnar grains will be more. Now if the thermal conductivity of the material if that is again more it will be inversely affecting the ratio of equiaxed to columnar grains.

So, as we discussed that if the ratio of g if the thermal conductivity of the mold will be more, in that case it will extract the heat quickly and that way you will have the setting of a temperature gradient, and it will lessen the gap between these freeze wave lines and that will basically be reducing. So, if that is more, if the connectivity is more in that case the ratio of equiaxed structure will be less. So, that is what it infers, then the last is inversely proportional to slope of solidus and liquidus lines.

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- Commercial alloys poured into castings and cooled in normal manner will exhibit columnar dendritic grains near surface and equiaxed dendritic grains near centre of casting.
- Ratio of equiaxed to columnar grains is
 - Inversely proportional to effective superheat
 - Proportional to freezing range
 - Inversely proportional to thermal conductivity
 - Inversely proportional to slope of solidus and liquidus line

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If the solidus and liquidus line slope is more, in that case ratio of the equiaxed to columnar grains will be less again it talks about if this slope is less in that case the separation will be more.

So, that way equiaxed to columnar grains will be more in that, but if the slope is more in that case the this ratio of equiaxed to columnar grains will be less. So, it is inversely proportional to the slope of solidus and liquidus line. So, this is how we see that how these are the different factors which affect this solidification of the material, you have factors like, you have the mold properties, you have properties of the material.

So, these are the main things which control the solidification process and as the solidification is very important because ultimately the quality of the cast depends upon how the solidification proceeds. We will study later on that how the solidification proceeds from the sides and also how the solidification gets basically finished, where what should be the last point where the solidification should finish. So, along with the solidification start and finish it is also important that where it should finish in the end where it should start. So, that is also important in the case of solidification, and that will be studied in the subsequent chapters, where we will study about the them the directional and progressive solidification and we will discuss that how these also are important.

Thank you very much.