Steel Quality Role of Secondary Refining and Continuous Casting
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Module - 06
Lecture - 31
Strength of Solidifying Strand

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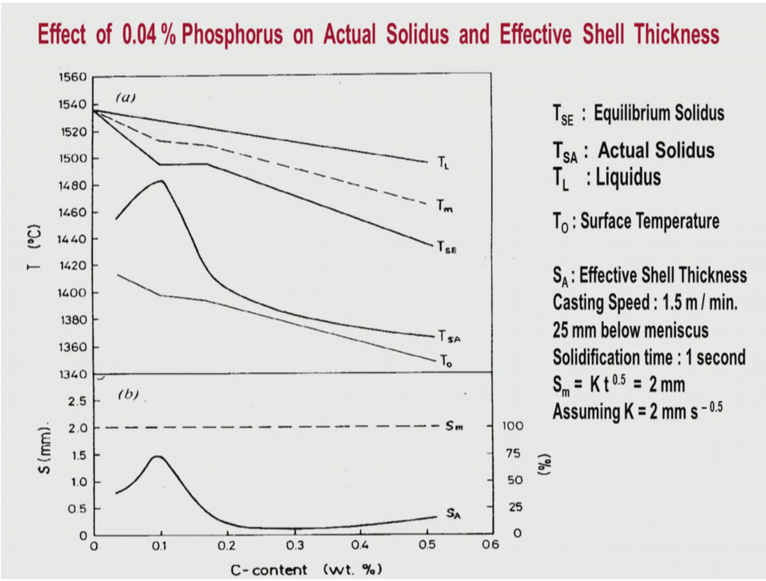

Some calculations have been made. Suppose we have 0.04 percent phosphorus in steel. So, what is its impact on segregation? What is its impact on actual solidus during solidification? What is its impact on the relative you know depth of the solid shell and the relative thickness of the mushy zone? Let us try to understand these figures.

Now all these have been calculated. So, these are calculated values and those have been plotted. So, T SE is a equilibrium solidus T L is a liquidus. So, with carbon how does it change? So, it is basically from the iron carbon diagram. Iron carbon diagram if you look at it how the liquidus temperature and the solidus temperature will change.

So, that is one: T SA is the actual solidus; this is actual solidus. Here the effect of micro segregation has been put into account. So, TSE is a theoretical solidus which you get from equilibrium diagram and T SA is the actual solidus which has been calculated based on micro segregation from modified Shell equation. Now at what stage of solidification do you calculate this that is important, because you know this is it is relative portion of the solidus this actual solidus temperature this will all depend on at what stage of solidification you are there. So, what has been done is- we have used a casting speed of 1.5 meter per minute 25 millimeter below the meniscus calculation has been done, at that point of time the solidification time was 1 second.

So, this is the 25 millimeter below meniscus and the shell solid shell thickness S M the theoretical solid shell thickness is as I have told you earlier it depends on the capital K which is the solidification considered into time to the power 0.5. So, since time is 1 second and k if you assume 2 millimeter per second to the power 0.05, so we can calculate the theoretical solid shell thickness which is 2 millimeter; this is theoretical. But actually what is the situation, it depends on the level of micro segregation.

Now the effect of 0.04 percent phosphorous: I have told you phosphorus is a very deleterious in steel if you have 0.04 percent phosphorus which is relatively high. We should not have so much of phosphors in steel, but for calculation purpose you have taken 0.04 percent phosphorus then let us see what happens. The actual solidus as I have told you it also depends on what is the mode of solidification.

As you are going from delta 2 gamma mode of solidification; that means, when you are going to more amount of carbon which is you will be having a delta mode of solidification you will find that the effect of micro segregation is quite high. Look at this figure T SA because of micro segregation the equilibrium solidus is coming down when you know here; that means, around 0.1 percent carbon where micro segregation is relatively less it comes down by amount by only about say 20 degree centigrade, but you come to a level of say 0.2, 0.25, 0.3; here the depth you know the deference is almost 100 degree centigrade.

So, from a level of twenty degree it is increasing to a distance of 100 degree that is 1 and number 2; what is it is impact on the relative depth of solid shell and mushy zone during solidification that is again important. I have told you 2 millimeter is the equilibrium solid shell thickness, but in reality look at the figures at point one, when segregation is minimum the solid shell is quite thick. It is I would 1.5 millimeter so; that means, from the theoretical value it is not much less, but look at this carbon concentrations 0.25; 0.3. So, here the solid shell is very thin is hardly 0.2 millimeter; that means, only 10 percent of the theoretical solid shell is actually solid and the rest is what rest is mushy zone it was mushy zone and the solid this together we will constitute the you know and of course, liquid is there.

So, the actual solid shell be thin becoming thinner means mushy zone becoming thicker the depth of mushy zone is more. So, what is the implication of this implication is the strength of the strand if the strand during solidification the solid shell is thinner and the mushy zone is thicker. So, the strand is hamming very small amount of solid during solidification the strength is consequently relatively low. So, this is the implication of segregation macro segregation of alloying elements on the impact on their impact on the strength of the strand solidifying strand during the stage of solidification.

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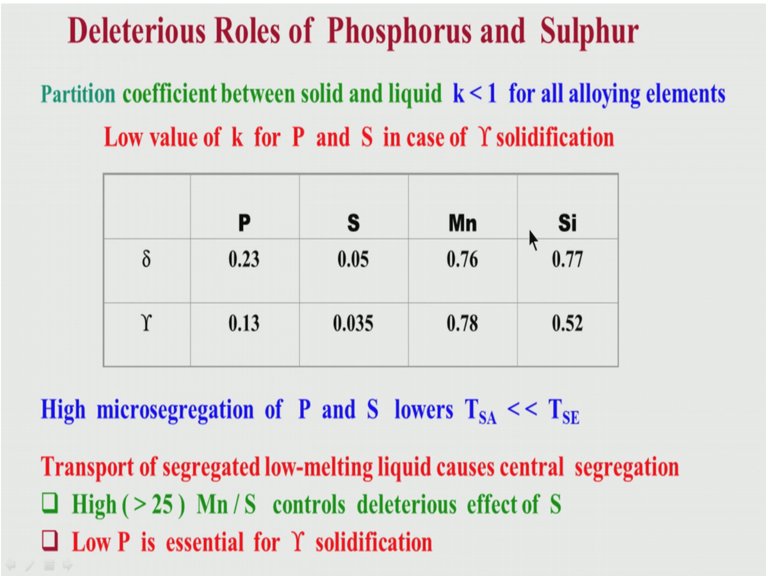

So, this is very important we have to remember; what is the impact of phosphorus you know, we had shown here that phosphorous the values are relatively less it is slightly higher compared to sulphur, but sulphur because a manganese, it is effects is taken care off to a large extent, but for phosphorus there is no element which can take care of it.

So, low phosphorous is essential particularly for gamma solidification look at gamma and delta for delta solidification the value of small case 0.23, but for gamma solidification this 0.13. So, it is still what? So, in case of gamma solidification; that means, when you are going to higher and higher carbon any steel which is having more amount of carbon we have to be more careful about the phosphorus because you know the extent of micro segregation will be more for gamma solidification.

So, phosphorus have to be less then only the affect of micro segregation will be relatively lesser. So, we have to remember; what is the dole of phosphorus why it is harmful? Why it is deleterious in causing micro segregation and if there is micro segregation. I have calculated the different values in the actual solidus to what extend it is coming down from the equilibrium solidus and if this is coming down means the difference between T L and T SA and then this depth of you know this depth; that means, a solidification range becomes quite wide if solidification range becomes wide means the mushy zone will become wider and the this difference between the surface temperature of the solid and the actual solidus this difference becomes less this difference is quite more you look at this figure is quite more at 0.1 percent carbon.

So, at 0.1 percent carbon the solid shell is relatively thick and the mushy zone is relatively thin, but as you are going to high carbon levels more than 0.2 what is happening; the actual solidus is coming down. So, the temperature interval is increasing temperature interval between liquidus and actual solidus this temperature interval was relatively less for 0.1 percent carbon not for 0.2, 0.3, 0.4, here you see the depth the difference between the T L liquidus and the actual solidus is quite high and the difference is quite high means the mushy zone will be quite wide the depth of mushy zone is wide and the solid shell is very thin. So, if the solid shell is thin look at this figure the solid shell thickness at a at a just you know depth of say 2 millimeter at a depth of say around 1 millimeter or 2 millimeter at a depth of 25 millimeter sorry 25 millimeter below meniscus at this depth what is the solid shell thickness is very very small.

So, the strand we will have much less strength there is a solid shell is less mushy zone is quite deep. So, the shell strength is also less. So, segregation is heavy amount of segregation is what is it creating is creating first lower solidus temperature. So, what is the consequence of this if the solidus temperature comes down the temperature interval for solidification between liquidus and an actual solidus this increases said point one was and this is relatively less and 0.3 percent it is quite high. So, because of this because of the suppression of the actual solidus what is the consequence consequences the mushy zone is quite deep.

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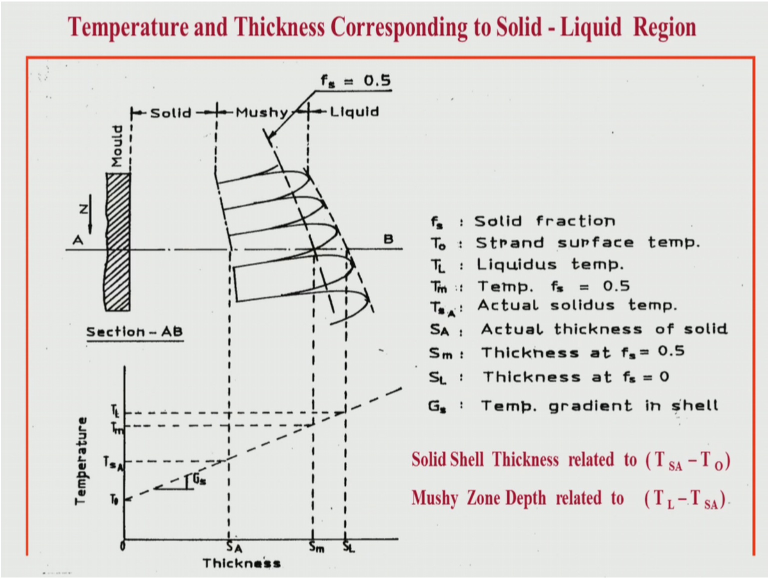

I think I have discussed this earlier if the actual solidus temperature this comes down the difference between the liquidus and the actual solidus increases if his increases the depth of these also we will increase this is directly proportional the mushy zone depth is related to the temperature interval between liquidus and actual solidus. So, segregation particularly say phosphorus it the higher amount of phosphorus you have there you too much of segregation because of that the actual solidus. We will be suppressed we will be depressed as we will come down.

So, the difference between the liquidus and the actual solidus, we will increase and because of this mushy zone depth we will become quite wide and the; if this decreases. So, this temperature interval is becoming lower the solid shell is become a relatively thinner this is what has been shown here actual calculation at 0.1 percent carbon and solid shell is relatively mode why because the temperature interval between the surface of the solid and the actual solidus is quite high and the temperature interval of solidification; that means, between the liquidus and the actual solidus is relatively less.

This difference is less this difference is more because of this difference is more means the solid shell will be more deep and the if these difference is relatively less mushy zone depth will be relatively less. So, at 0.1 percent carbon you see; what is happening. Solid shell is relatively more deep mushy zone is quire less deep, but look at what is happening here 0.2 to 0.3 percent carbon the actual solidus is has been depressed because a micro segregation because of austenitic solidification. So, temperature interval between the liquidus and the actual solidus is quite high and the temperature interval between the surface of the solid and the actual solidus is quite low this is quite low this is quite big quite large.

So, the depth of the; you know mushy zone is quite big and the solid shell is quite thin this is the consequence of high segregation of phosphorus the all alloying elements will contribute their; you know part in segregation. So, it depends what are the small k values what are the; you know the diffusion coefficient in the solid. So, all these factors we will finally, give us a relative amount of micro segregation relative amount of segregation of the alloying elements it depends exclusively on the small value of k. Small value of k is very important. Small value of k means more segregation small value of k in gamma solidification you see gamma solidification this k values are less so; that means, the segregation of sulphur phosphorus will be more for gamma solidification as such values are low whether is delta and gamma and between delta and gamma; gamma again are low gamma values are again and low.

But as I have told you there is a Sevier for sulphur manganese is the Sevier manganese can help reduce the effect of the bad effect of segregation of sulphur, because it combines with manganese is combines with sulphur forming manganese sulfide and iron sulfide cannot form because iron sulfide is the culprit that that creates lower solidification temperature. So, if you do not have manganese then sulphur we will pose a problem if you do not have adequate amount of manganese sulphur we will pose a problem, but since there is no such Sevier for phosphorus unfortunately.

So, phosphorus value has such has to be low. So, that segregation effect is relatively less here the quantitatively some calculations have been done just to show; what is the you know level of impact of phosphorus how does it affect the actual solidus temperature how does it affect the solid shell thickness you know during the course of solidification for different level of carbon different level carbon basically indicates different solidification mode that I have explained earlier in the last you know discussion.

So, all these are related how the alloying elements are controlling the solidification mode they are controlling by controlling the carbon equivalent in plain carbon steel; that means, steels which you have just carbon iron carbon diagram is the criteria in low alloy steels we have to calculate carbon equivalent; that means, how the alloying elements like manganese silicon and chromium nickel what about at their present their small amount in low alloy steels how they are affecting the carbon activity in solidification so that we will have impact on the carbon equivalent. So, carbon equivalent if you calculate depending on the chemistry of the steel. So, then we know how the steel we will solidify weather through delta or through gamma or in mix solidification mode at what temperature you know the solidification is complete.

So, these are all important these are all important issues to understand what we will be the impact on steel quality because why I am again and again repeat what is the segregation lowered is the T S; that means, the actual solidus temperature is lowered due to segregation more segregation means this value will be lowered further and if this is lowered the temperature interval for solidification increases temperature difference between the liquidus and the actual solidus increases as such; it increases with normal carbon you know from equilibrium iron carbon equilibrium dynamic on find, but due to other alloying elements present due to micro segregation all alloying elements will cause you know suppression of actual solidus the actual solidus will be lower compute to the equilibrium solidus, but the carbon concentration the mode of solidification will tell us; what is that extent quantitatively what is the extent at point one percent carbon.

The effect of micro segregation is minimum, but at 0.3 percent carbon 0.25, 0.3, 0.4. It is quite big; quire large. So, the shell solid; shell thickness is hashed for 0.1 percent carbon and relatively lowered for 0.25, 0.3, 0.4 percent carbon this is very important to remember. So, 0.1 percent carbon micro segregation is relatively less solid shell during solidification it is relatively thick mushy zone is relatively thin, but for higher carbon say 0.25, 0.3, 0.4, 0.5 just the reverse is true this actual solidus is much lowered. So, the temperature interval for solidification is much higher because of this the solid shell is quite thin and the mushy zone is quite thick. So, this has large implication large consequence on what is the strength of the shell strength of that solidifying strand that is important to understand.

Here at a particular level calculations have been made. So, similarly calculations can be made at different level different stage of solidification. So, we can know; what is the extent of solidification. It is possible to calculate this. I have explain to you how the different temperatures; that means, particularly the actual solidus temperature has influence on the depth of mushy zone and the thickness of the solid shell the lowered is the value of actual solidus this temperature interval between liquid; liquidus an actual solidus full increased lower this value lower the actual solidus means T L remaining more or less constant more will be this value more will be this value means the mushy zone also will be more.

So, that is why I am again and again mentioning the effect of micro segregation and is to not only create is zone of higher segregation; that means, the area which is solidify at the last which we will have more segregation that is number 1 impact. Number 2 an equally important impact is the mushy zone depth is increasing and the solid shell thickness is decreasing T SA decreasing means this depth is increasing T SA decreasing means the difference between T SA and T 0; that means, the surface temperature was solid.

This is decreasing. So, solid shell thickness is decreasing mushy zone depth is increasing because of segregation. So, this we have to remember what is there is impact on the quality.

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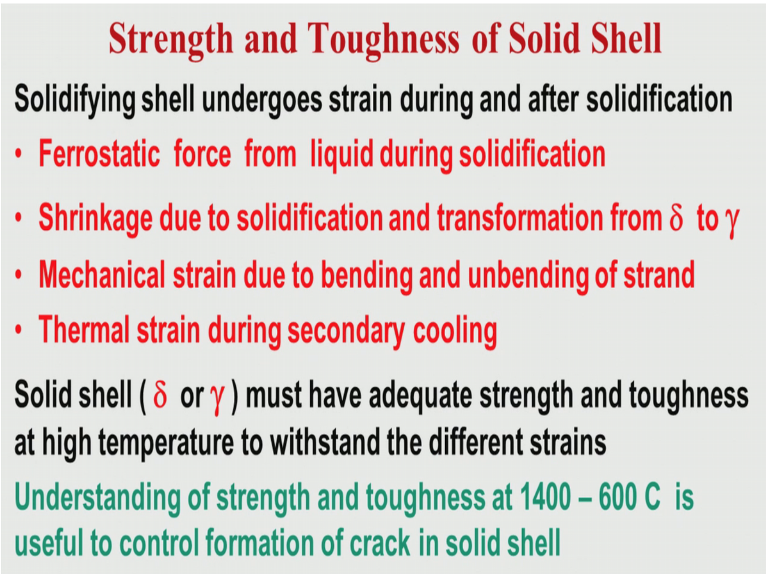

Now I will just start the discussion in today that strength and toughness of solid shell why this is important solidifying shell under goes strain during and after solidification we have to remember thus when solidification is taking place first weather solid shell is delta or gamma that is important. Why it is important because the strength and toughness of delta and gamma at high temperature and not identical they are different. So, what is the solid shell is it delta ferrite or austenite that is important first also the solid shell is undergoing lot of strain. Now what are the strain? Let us try to see during solidification; there is a ferrostatic force from the liquid during solidification ferrostatic force is from the liquid which is still they are during solidification.

After solidification; there is no liquid, there is no ferrostatic force during solidification there is lot of liquid. So, ferrostatic force from the liquid we will push the solid shell. So, you on the solid sell you have some force acting on it; it will try to push the solid shell to us the mold the direction is also known ferrostatic force. So, there is some strain on it number one number 2 shrinkage due to solidification first. Whenever there is a solidification; there is shrinkage there is a volume change due to volume change there is a density change.

So, there is a volume change there is a; that is why there is a shrinkage lower volume is there is a shrinkage. So, the due to shrinkage again they will be a force on the solid shell number one again if there is a transformation from delta to gamma; that means, initially delta is forming and then delta is transforming to gamma then this transformation to delta to gamma also cause a transformation stress strain.

So, due to shrinkage liquid to solid whether delta or gamma there is a strain shrinkage strain then if the transformation takes place initially to delta and then to gamma then we were this transformation take place again this is important this is I will come to you later. So, because of this transformation there is against strain. So, initially there was a ferrostatic force from the liquid then during solidification. Again there is a shrinkage and there is a transformation if there is a transformation for delta to gamma depending on a particular chemistry again there is a shrinkage and there is a strain. Now there can be mechanical strain due to bending and unbending of strand these I have explain to you earlier that when whenever there is a bending of the shell you know first the strand is coming out vertically from the mold if the mold is vertical if you are using mold vertical mold the strand solidifying strand is coming out vertically.

But it has to be made horizontal finally, so, how it is made. So, first if there is a vertical mold the strand has to be initially given a bending and then there has to be unbending this 2 combination. We will make the strand horizontal. So, because of this bending and unbending the solid shell solid portion of the shell we will have some strain on it because of bending you know the inner radius the shell are the inner radius we will have something the shell are the outer radius will have adjust the reverse, if it one is tensile the other will be compressive if there is bending there is something stain and there is unbending there is again the reverse strain. Now for a calved mold you need not bend the strain wend is coming out because it is already coming out with an angle. So, you need not bend it, but it is necessary to unbend to unbend the strand to make it horizontal.

Otherwise you will go on like a circle which we cannot allow the strand has to be made finally, horizontal. So, that we can take the cast product you can cut that cast product. So, this is the necessity. So, if you have a calved mold only unbending is necessary. So, during unbending again there will be some strand there will be some strain in the solid shell at the inner radius something at the outer radius something I have discussed earlier these. So, what I am trying to tell here is the mechanical strain this is the mechanical strain due to bending and unbending of strand. So, these are you know strain because of shrinkage solidifications strain because of transformation ferrostatic force be strain because of ferrostatic you know reaction. Now there can be a thermal strain during secondary cooling after the strand comes out from the mold you have to use water for secondary cooling water is impinged on the strand surface both are the inner radius and the outer radius you must spray water or air messed. So, because of that there is a thermal strain why the surface is the surface is exposed that the surface is cooled relatively more the interior is hot. So, because of temperature difference due to the secondary cooling that is a thermal strain.

So, you can make out. So, many strains are operating on the solid shell on the strain unlike casting. So, that is why during continuous casting we have to be more careful about these strains. We have to be more careful about the strength and toughness of the solid shell. So, that is why what I am telling here you look at it the solid shell whether it is delta or gamma after solidification is complete; what is the constituent? Is it delta ferrite or gamma? This must have adequate strength and toughness at high temperature to with stand the different strains high temperature. Basically what I mean during solidification and at temperature lower than solidification also that is why what is important is to understand the strength and toughness of the solid shell at this temperature interval at 1400 degree centigrade the solidification is more or less you see at different depend on the chemistry when the solidification we will be complete.

So, say when low carbon solidification relatively complete at 1400 degree centigrade at higher carbon solidification we will complete only at still lower temperature solidification continues. So, what is important is from 1400 to as low as 600 degree centigrade. Why this is important because when solid has already formed, then also the shell strength is important because lot of strength and toughness is important because lot of strains are you know created. So, the solid shell has to with stand those strains otherwise they will be crack formation there will be a; you know formation of some defects if the shell cannot with stand this strains. So, this understanding of strength and toughness at high temperature is very important to control formation of crack in solid shell solid shell should have adequate strength and toughness.

During solidification as I have told you the mode of solidification the chemistry the extent of segregation we will determined what is the actual thickness of solid shell. So, during solidification solid shell thickness, you can get from segregation extend of segregation, but after solidification; that means, when the solid shell is hundred percent you do not have any liquid do not have any mushy zone. So, there also the strength of the shell is important solid shells toughness of the shell is important because if the strength is there, but if there is no toughness at particular I will come to it later on at particular temperature ranges the toughness is relatively low we call it you know brittleness at certain temperatures if it is. So, so if there are strain on the shell; that means, there can be formation of crack.

So, it has to be understood very clearly that at what temperature what is the constituent of the solid whether is delta or gamma and what is the strength and toughness of the solid at different temperatures. So, that whatever strains at generating are getting created getting impinged on the solid shell whether the solid shell is capable of withstanding those strains. It is very important to understand that if it can with stand there will be no crack the continuous cast product we will be devoid of any defect no crack formation, but if it cannot if the solid shell cannot with stand some of the strains whether it is ferrostatic, whether it is shrinkage, what is mechanical strain thermal strain they are getting created at different temperature zone all are not you know where it at all temperature zone. So, at different temperature zones different strains are getting created for example, ferrostatic force it is valid only till solidification after solidification which is no longer there and solidification shrinkage it is valid only during solidification.

After solidification then it is more solidification shrinkage this transformation to delta to gamma it depends this shrinkage from delta to gamma we will be effective depending on when it is taking place whether during solidification or after solidification this is very important then mechanical strain due to bending and unbending, I have told you, it again depends on at a certain you know location in the caster; that means, at a certain depth in the caster consequently; that means, at certain temperature interval in the solid shell.

So, it is very important to understand at what temperature interval you are using bending and unending whether the strain mechanical strain that is getting generated whether the shell can which stand that strain or they will be some crack formation there maybe bulging crack there may be other crack. So, this is very important to understand when then the solid shell whether it is delta or gamma they have adequate strength and toughness at high temperature high temperature means temperature from say 1400 to sixteen hundred it must have a adequate strength and toughness then only it can with stand a different strains get in generated at different temperatures.

So, at the you know from the depth suppose you have casted solid steel say and at the interface a you know at a intersection if you look at the intersection we will find at certain depth there is some crack. So, why does it form at certain depth because whether it formed during solidification whether it has formed after solidification; solidification was complete, but then because of the mechanical strain due to bending or unbending no those cracks I have formed it is important to understand from the crack what is the type of crack whether it has form during solidification at what stage of solidification all after solidification this is important.

Thank you very much.