Steel Quality Role of Secondary Refining and Continuous Casting
Dr. Santanu Kr Ray
Department of Mechanical Engineering
Indian Institute of Technology, Madras

Module – 07
Lecture – 36
Role of Chemistry on Bulging or Depression Tendency: Part I

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Bulging or Depression Behaviour based on Solidification Characteristics

	0.02 – 0.05 % C_{eq}	Peritectic ~ 0.1 % C_{eq}	0.2 – 0.4 % C_{eq}	> 0.5 % C_{eq}
Solidification Mode	Entirely δ	δ till f_s ~ 0.75 $\delta + \gamma$ at f_s : 0.8 – 1.0	δ till f_s ~ 0.3 $\delta + \gamma$ at f_s : 0.3 – 0.5	Entirely γ
Solid Shell	Thick but weak	Thick and strong	Thin	Thin but strong
Mushy Zone	Narrow	Narrow	Deep	Deep
$\delta \rightarrow \gamma$ around Solidus	---	High	---	---
Mould Sticking	High	---	High	High
Bulging	High	---	High	High
Depression	---	High	---	---

Let us try to now see for different carbon equivalent what is the behavior of the solid shell; whether there is a bulging or there will be depression based on the solidification characteristics let us try to understand. So, let us first try to understand very low carbon equivalent, chemistry corresponding to say 0.02 to 0.05 percent carbon equivalents. What happens in this temperature in this chemists range as I have told you solidification mode will be entirely delta there is no question of gamma during solidification for this chemistry. So, solidification mode is entirely delta. So, solid shell what is the solid shell? it is delta it is thick, but this is weak why this is weak because the strength of delta is much low compared to the high temperature strength of gamma austenite.

Delta ferrite has a high temperature strength which is one fifth of the high temperature relatively speaking it is one fifth of the high temperature strength of austenite. So, if we have total gamma delta ferrite solidification for very low carbon. So, what is happening? The solid shell is delta during and after solidification slightly below solidification also its delta and this delta is relatively thick because micro segregation is low. So, delta will also be relatively more in during solidification, but this is relatively weak because of the high temperature strength of delta ferrite is low. Now mushy zone I have told you because micro segregation effect is less mushy zone is narrow. This delta to gamma around solidus there is no delta to gamma transformation around solidus because delta to gamma we will form only at lower temperature; that means, after solidification much after solidification.

So, what is the consequence? Consequence this because of this weak shell though it is thick, but it is weak. So, this sticking tendency will be more, there is no delta to gamma around solidus; that means, the you know bulging tendency or sticking tendency will be there, but depression tendency will not be there; that means, shell shrinkage relatively will be less because delta to gamma transformation is at much lower temperature and not in the you know crucial little temperature zone.

So, what is happening sticking tendency is high, bulging tendency below the mold will be naturally high, sticking tendency mould sticking tendency within the mould region will be high. So, for low carbon concentration it is a sticking and bulging type of solidification behavior. Now let us see what is happening for a carbon concentration what we call the peritectic; that means, around 0.1 percent carbon I am telling it is around 0.1, but actually it is maybe 08 carbon 2 may be 1.5, 1.6 carbon. 07 to say 1.7 carbon or carbon equivalent depending on whether you are talking about plain carbon steel or low velocity.

So, this carbon concentration we call it a peritectic chemistry. So, what is happening initially solidification is delta, and is delta is available that mean delta is present till solid fraction around 0.75 where slightly lower than that. So, gamma del it goes from delta to liquid plus delta to liquid plus delta to plus gamma; that means, the peritectic reaction is starting at a solid fraction of say 0.8 and the whole delta to gamma transformation the peritectic transformation is taking place in the solid fraction of 0.8 to 1 which I have told 0.9 to 1 is the crucial brittle temperature zone. Solid fraction between 0.9 to 1 is the temperature zone which is we call it a brittle temperature zone because the ductility of the shell solution is 0 in this temperature zone. There is some strength in the shell, but the ductility is 0.

So, when whatever strain is forming due to you know shrinkage of solidification or delta to gamma transformation. So, this is happening in the crucial brittle temperature region of 0.9 to 1. So, what is going to happen you see here delta to gamma around solidus is relatively high, almost entire delta to gamma takes place in this temperature region. So, the shrinkage is quite high if the shrinkage is quite high you have depression. So, this particular chemistry we have depression. So, we have a thick shell and also at the end of the solidification why at the end given at 0.75 all around 0.8 only (Refer Time: 05:54) started forming and towards the end of solidification is totally austenite.

So, therefore, towards the end of the solidification the solid shell is very thick and strong. So that means, it can withstand sticking and bulging, but that is why the sticking and bulging tendency is not there at all, but it has the reverse the other type of solidification characteristics; that means, it will have depression because of high shrinkage. Shrinkage strain is quite high because this delta to gamma is taking place entirely in this brittle temperature region. So, very low carbon it is sticking and bulging tendency around 0.1 percent carbon equivalent, I am telling around it may be from 07 to 0.17. So, it is a near the peritectic chemistry we call it around 0.1 we call it a peritectic so called. So, here that depression tendency is very high.

Now, let us go to a carbon concentration above this say 0.2 to 0.4 what is happening. Here delta initially is a delta transformation steel delta l transformation will be there during solidification, which will be present till about 0.3 percent solid. So that means, around 0.3 percent of solid fraction delta is starting transformation to gamma due to peritectic reaction. So, in this carbon concentration initially there is delta formation, but delta to gamma transformation is taking place around solid fraction of 0.3 to 0.5; that means, it is taking place above that brittle temperature region which is 90 percent solid fraction to 100 percent solid fraction it is taking place above that.

So, delta to gamma around solidus is not there it is taking place about that here around 0.1 percent carbon it was maximum around the you know solidus temperature for low carbon, 0.1 it is lower than solidus temperature at 0.1 percent carbon it is near the solidus temperature at 0.2 to 0.5 which is above the you know 0.9 to 0.1 that is much of the solidus temperature around 30 percent to 50 percent solidus. So, here also delta to gamma is taking place higher and the solidus compression temperature.

So, here also what is happening because of micro segregation because too much of delta is forming, you know at the end of circulation. So, we have a thin solid shell mushy zone is more quite you know big. So, the mushy zone is dipped and the sticking and bulging tendency also relatively high. So, if you go to above 0.5 percent carbon equipment, why above 0.5? This is the you know zone of peritectic concentration zone is about 0.5, 0.1 to 0.5. So, when you are taking a temperature which is above 0.5 percent carbon.

So, initially there is delta formation not no delta formation initial there is no delta formation, there is only austenite formation. So, here for more than 0.5 percent carbon or carbon equivalent, we are totally gamma or austenite solidification initially austenite is forming during solidification and solidification of course, we have total austenite. So, here what is the you know solid shell it is thin why because since solidification is two delta as I have told you the micro segregation effect for all (Refer Time: 09:51) elements particularly phosphorous sulphur will be more in the delta solidification in that gamma solidification region austenite solidification.

So, we have a think solid shell, but it is relatively strong because it is austenite whose strength at high temperature strength is more than the that of delta ferrite. Here it was thick, but it was a relatively weak here it is thin, but relatively strong, but it is then due to micro segregation lot of micro segregation. So, the mushy zone here is deep, mushy zone for you know higher carbon you see it is deep because of micro segregation, here for low carbon it is quite narrow.

So, because the mushy zone is deep you know this solution will be thin relatively. So, what is happening here again since this is thin solid shell is thin. So, it cannot withstand the ferrostatic pressure, the ferrostatic pressure will push it towards the mold. So, is again a mould sticking for high carbon and when it come out of the mould there is a bulging tendency; that means, the two are you know solid shell at the two ends of the near the you know 2surfaces of the mold when it is coming out of the mould, there is a tendency for bulging ferrostatic force will try to budge it. So, this is relatively high bulging.

So, what is clear from this is that, when you have a peritectic chemistry we have high depression tendency when you have very low carbon we have a sticking and bulging tendency, when you have a high carbon; that means, 0.2 and above again we have a sticking and bulging tendency the reason is different here we have a bulging or sticking tendency because of thin shell thin solid shell thin solid shell is austenitic, but since it is thin it cannot resist the ferrostatic force. So, it goes towards the mould and causes bulging when it comes out of the mould, but here there is not much of micro segregation, but it is delta even after solidification for certain temperature it is delta, which is a relatively lower strength at high temperature compared to austenite.

So, the shell is weak, but it is another also shell is thick, but it is weak because of because it is delta it is weak. So, because it has low strength it can resist ferrostatic force strength. So, the question is consequences it will be sticking or budging tendency. So, only for the near the peritectic chemistry; that means, chemistry near around 0.1 percent carbon equivalent says zeroes 0.072 0.1 7 carbon we have depression tendency. All other chemistry whether it is low carbon or high carbon we have a sticking or bulging tendency for different reason of course, but nevertheless the final effect is we are sticking and bulging for very low carbon and high carbon chemistry's only around 0.1 percent carbon we have depression tendency.

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Bulging or Depression Behaviour based on Solidification Characteristics

	AISI 430	301	304	316	310 S
Solidification Mode	Entirely δ	Entirely δ	δ till $f_s \sim 0.75$ $\delta+\gamma$ at f_s : 0.8 - 1.0	δ till $f_s \sim 0.3$ $\delta+\gamma$ at f_s : 0.4 – 0.8	Entirely γ
Solid Shell	Thick but weak	Thick	Thick and strong	Moderate	Thin but strong
Mushy Zone	Thin	Thin	Thin	Moderate	Thick
$\delta \rightarrow \gamma$ around Solidus	---	Minor	High	Moderate	---
Mould Sticking	High	---	---	---	High
Bulging	High	---	---	---	High
Depression	---	Minor	High	Moderate	Minor

So, now let us go to stainless steel, what I have talked is basically the plain carbon or the low (Refer Time: 13:33) I have told you around 0.1 percent carbon we have depression tendency, for very low carbon or very high carbon we have moulds sticking and bulging tendency when it comes out of the mould and there will be bulging. Because of either soft shell, but or soft shell for very low carbon and thin shell for relatively thin shell for high carbon. So, there is a sticking or bulging tendency for very low carbon and very high carbon only for around 0.1 percent carbon it is a depression tendency surface will have lot of depressions surface is not uniform this is no surface is rough we have a rough surface of the solid shell for 0.1 percent around 0.1 percent curve.

Now, let us see what happens for the stainless steel. I have told you I have tried to explain when we are talking about the stainless steel like how the solidification is taking place I have my explained yeah.

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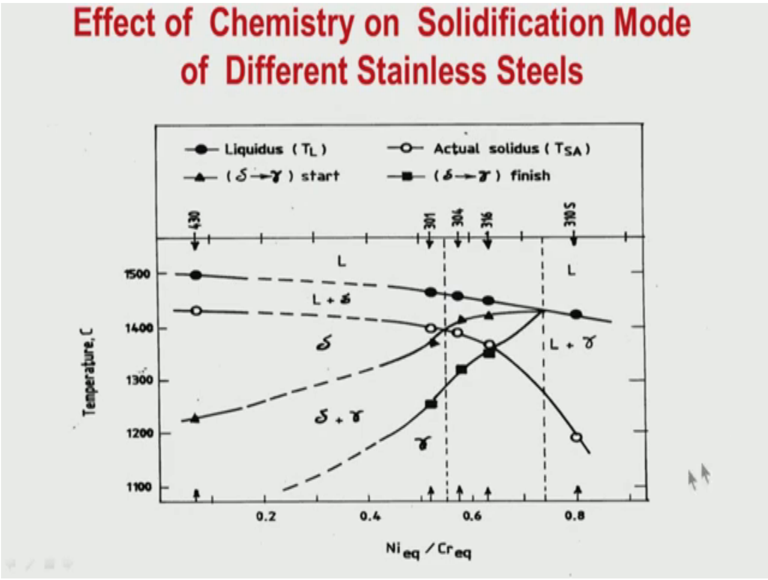

Let us see this, here we are plotting the chemistry along nickel equivalent by chromium equivalent I have told you that since it is

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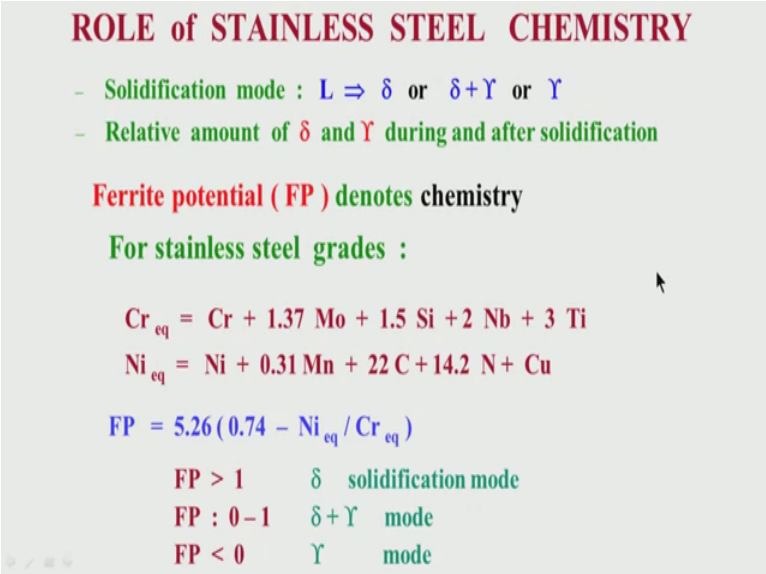

Stainless steel there is lot of chromium some of the man nickel also. So, normal iron carbon diagram or pseudo iron carbon diagram or carbon or carbon equivalent cannot explain the chemistry. Here the chemistry has to be explained through a ratio of nickel equivalent by chromium equivalent. Nickel equivalent is basically here all elements clubbed together along with nickel which is an austenite stabilizer, and all elements which are ferrite stabilizers have been clubbed together with chromium which is again a ferrite stabilizer.

So, chromium equivalent and nickel equivalent we find out from the base chemistry. So, then the ratio of this will determine how the solidification is taking place. Let us look at for 430 when the nickel equivalent by chromium equivalent is very low, solidification is through delta ferrite only it is like very low pulse on carbon, what happened for very low pulse on carbon same thing is happening during solidification for peritectic grades like 430, initially that is liquid and then liquid plus delta solidification is complete only through delta, and this delta to gamma transformation is taking place at quite low temperature you know depends on what is the nickel equivalent; which come here which is very low this gap is more. As we are going to have a (Refer Time: 16:26) nickel equivalent by chromium equivalent; that means, equivalent to higher and higher carbon equivalent for plain carbon or low (Refer Time: 16:32) this delta to gamma formation will be relatively enhanced relatively high temperature, but solid if what is important to remember is the solidification is totally true delta ferrite.

Now, what is happening to say 301? Which is austenite at room temperature, but high temperature what is happening let us see initially it is liquid it then transform a then the solidification is through delta only liquid plus delta, when the solidification is complete then also we have a delta. So, delta to gamma this is the delta to gamma line it is taking place below solidification completion. So, solidification is complete only through delta and at slightly lower temperature to that delta to gamma transformation is taking place in solid state. So, during solidification there is more delta to gamma formation.

Now, I have given putted a I have put a rather you know dotted line here, what is this you know nickel equivalent chromium equivalent. It is 0.55 why I put because you see this changeover between delta to gamma line and solidification completes line. So, what is the implication? Implication is beyond; that means, above 0.55 nickel equivalent chromium equivalent, this delta to gamma transformation is taking place in solid during solidification that is before the completion of solidification this as started this is very important.

So, in 304 what is happening? Just see 304 this initial to delta liquid to delta then delta to gamma transformation takes pl ace before the completion of solidification. So, do delta to gamma is taking place around say 0.8 percent completion of solidification, when the solid fraction is say 0.8 delta to gamma started transforming. So, again it is like you know around 0.1 percent carbon only; that means, 304 delta to gamma transformation takes place towards the end of solidification and what is the end of solidification that region is the brittle temperature region. So, we have to be careful about this particular grade of stainless steel.

Now, 316 where the nickel equivalent then by chromium equivalent is more than is about is about 0.65 or. So, 0.63 may be. So, what is happening here? Initially again delta, but delta to gamma is taking place at much higher temperature; that means, when the solid fraction is about 0.3 or so. So delta to gamma has started forming and most of the delta to gamma is over by the time we come to the end of solidification. So, there is a change between 301, 304 and 316. 301 delta to gamma is taking place after solidification is over, 304 delta to gamma is taking place towards the started taking place towards the end of solidification, 316 delta to gamma has started taking place at much you know earliest day of solidification.

So, there is some difference as between 301 301 and 316. Now let us come to a chemistry which is above this 0.74 which is equivalent to 0.5 yeah 0.5 percent of carbon equivalent which I had mentioned. Beyond this that means, when nickel equivalent by chromium equivalent is above 0.74, what is happening? Now solidification is through austenitic mode only there is no delta formation at any stage. So, solidification is through austenite and when it is completed then also it is solid austenite. So, 310 again one popular stainless steel grid, here because the nickel equivalent by chromium equivalent which is around 0.8 is more than 0.74 this dotted line, this transformation is taking place sequence of solidification is through austenitic mode only there is no delta.

So, if we understand this cultivation modes for the different stainless steel chemistry's, I am mentioned for 430 it is totally you know peritectic, and austenite formation is much lower temperature, 301 again it is peritectic solidification, austenite solidification starts below the solidus temperature when solidification is complete after that only delta to gamma is taking place; that means, that transformation induced is in solid state not in the liquid state, 304 delta to gamma transformation has started towards the end of the solidification. So, this is a very you know crucial chemistry which is very vulnerable to the for it the delta to gamma transformation takes place and you know during the end of the solidification. So, this is a risky chemistry we have to be careful on that.

So, 316 that risk is there, but relatively less because is delta to gamma is taking place has started taking place or much higher stage of solidification, 310 s total austentic solidification there is no delta to gamma only gamma solidification. So, a difference in solidification mode I have tried to explain from this different you now for the different chemistry's.

Now, let us try to see how does it the solidification is taking place or what are the implication on the sticking or bulging tendency, which I have told is very important yeah. There is bulging or depression behavior based on solidification characteristics for stainless steel. So, 430 I have told you the solidification mode is entirely delta solidification is taking place to ferrite only. So, this is one important observation for 301 again it is delta. So, this is delta to gamma around solid that is much less here towards the slightly lower than solidus. So, it is very minor it is almost 0, here it is 0 it is almost 0, 304 it is delta to gamma you see delta is present till around 0.75 and delta to gamma for 304 is taking place mostly in this temperature region.

So, towards the end of solidification you have lot of delta to gamma transformation taking place. 316 as I told you delta is present initially delta and is present only up to 30 percent of solid fraction. Above that we have gamma transformation and delta to gamma is taking place above this you know crucial temperature brittle temperature region between corresponding to 90 percent 100 percent solidus. So, this 316 delta to gamma is taking place not around solidus it is above solidus before the completion of solidification 310 s of course, as I have told you is the entirely austenite solidification therefore, there is no question of delta to gamma transformation at all at any temperature.

Now, what is happening to the solid shell like very low carbon as I have told you here also for this peritectic grade for 30 that mean nickel equivalent and chromium becomes very low, entire is entirely through delta and delta to gamma take place at much lower temperature. So, in solid state the solid shell is therefore, thick because micro segregation is quite low, but it is weak why it is weak because it is delta ferrite whose high temperature strength is relatively low compared to that of austenite.

So, like very low carbon this 430 peritectic grade is also the solid shell is thick, but weak during solidification and the mushy zone is relatively thin, but since the solid shell is weak it is difficult for it to withstand the ferrostatic pressure, and the shrinkage is also less. So, therefore, is sticking and bulging tendency will be relatively more depression tendencies not at all there. So, because of the you know weak shells solid shell which is delta, even after solidification it is delta for quite some time for quite a temperature lower temperature delta stable.

So, the delta to gamma transformation takes place at much lower temperature. So, for a quite a big range of temperature we are having a weak solid shell because it is delta ferrite. So, because of this there is a tendency for mould sticking within solids or mithin you know and mould, and below the mould there is a tendency for bulging. So, because it is soft the solid shell has low strength at high temperatures. So, bulging tendency high. So, therefore, we have to be careful about that, because you know whatever strain will be there at different temperatures the possibility of causing crack at the interior of the solid shell. So, we have to be careful about that 301 entirely delta solid shell is thick, but it is not very weak because towards the end of that just after the solidification it is transforming to austenite.

So, austenite high temperature strength is relatively high. So, I have not mentioned it is thick it is, it is not weak it is thick, but is it a relatively strong. So, mushy zone here is again relatively thin during solidification because the solidification is entirely through delta ferrite. So, therefore, the chance of micro segregation incidence of micro segregation is relatively less. So, mushy zone is thin, solid shell is thick. So, here also the tendency of mould sticking and bulging is not there, but there is a minor depression almost very because of this delta to gamma towards the end of the solidification slightly lower than that it is almost negligible here it there was no depression at all here it is very minor. A 304 is like our 0.1 percent carbon steel what is happening you see. Delta is present steel about 0.75 percent of 0.75 solid fraction; that means, 75 percent of ferrite solid is there only below that; that means, gamma I started taking place around 0.8 to 1 percent solid fraction.

So, what is happening here 0.9 to 1 as I told you is the crucial zone of brittleness temperature zone. So, therefore, this particular grade we will have a tendency to form crack near the solidus completion because delta to gamma around this is very high delta to gamma is very high. So, this will have implication on the solidification characteristics and crack formation here also mushy zone because initial solidification is two delta. So, relatively thin, but here depression tendency is very high because delta to gamma is taking place in the crucial brittle temperature region. So, depression tendency is high and now there is more mould taking on a bulging. Depression tendency high means surface will have lot of depression you know it is uneven surface, if you have uneven surface because of that heat transfer get affected.

So, the grade size of the dendrite they become relatively thicker compared to other chemistries. So, depression in a many implications on quality, 304 is like 0.1 percent carbon we have rough surface we have depression, we have coarse grain we I will come to it later on. 316 what is happening delta is present only up to 30 percent of solid fraction. Lower than that gamma has started forming and gamma will be complete you know before the crucial brittle temperature region therefore, the relative amount of depression is there, but it is less compared to 304. The delta to gamma around solidus is moderate that is why depression also will be moderate mushy zone is also moderate here it was thin, but it is slightly increasing thickness why because the gamma transformation is taking place in the solid state at. In during solidification at relatively higher solid fraction.

So, solid shell is you know more or at in both respects from the thickness point of view from the strain point of view. 310 s as I have told you it is solidification is entirely through austenite, and if it is entirely through austenite you have a lot of micro segregation. So, the solid shell is thin, but strong because it is austenite will high temperature strength is relatively more, but because it is thin and I have told you the thickness if it is thin the you know strain is the inversely proportional to the square of the thickness or things if the thin shell it cannot withstand even it is slightly strong it cannot withstand the ferrostatic force. So, the sticking strain and bulging strain will be quite high. So, the tendency is it will have mould sticking tendency, it will have bulging tendency, depression is almost not there at all.

So, if you try to understand what are the solidification behavior and consequent to that whether they will be bulging whether there will be depression what chemistry will have depression what chemistry will have bulging. So, I have mentioned that for plane carbon and low alloy steels the chemistry around 0.1 percent carbon or carbon equivalent it has depression very low carbon and very high carbon they have sticking and bulging tendency the behavior is similar for stainless steel, but of course, here carbon is of no consequence here the nickel equivalent by chromium equivalent is representing the chemistry. So, 304, but the nickel equivalent by chromium equivalent is around 0.55 0.56, here it has lot of depression tendency. For low nickel equivalent by chromium equivalent for 430 and 301 depression is not there only sticking and bulging.

Similarly, for high carbon or rather not high carbon high nickel equivalent by chromium equivalent; that means, when the solidification is only through delta only (Refer Time: 33:32) that austenite we have high tendency of mould sticking and bulging depression is not there at all here the mushy zone will be thick during solidification and we have a very thin solid shell during solidification which cannot resist the ferrostatic force or strain. So, the bulging strain sticking strain is more actually we have mould sticking and budging tendency.

Thank you very much.