Welding of Advanced High Strength Steels for Automotive Applications
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Lecture - 17
Elemental Behaviour During Welding of Advanced High Strength Steels

So, we looked at the role of alloying elements during solidification of whirl pool in a typical trip steel composition.

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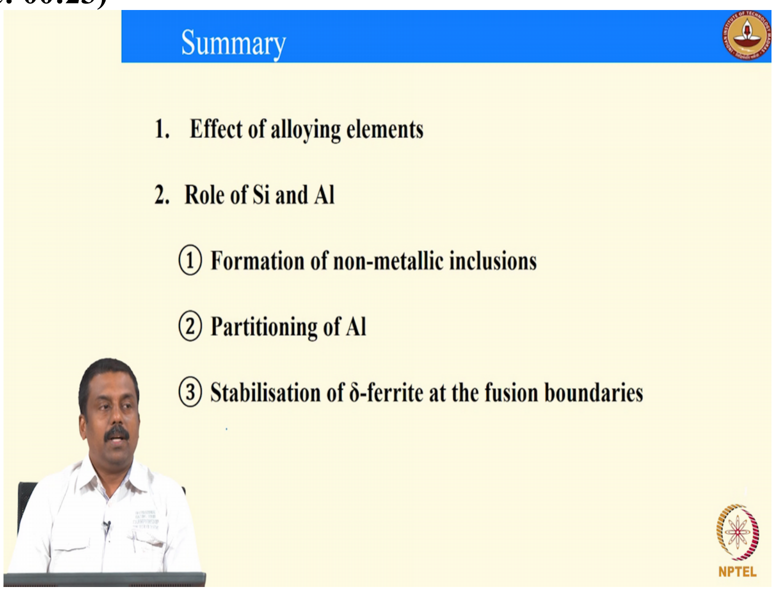

So, if we looked at two important alloying elements that are added in trip steel to stability austenite, the silicon aluminum. So, the silicon aluminum additions to the material chemistry leading to the formation of nonmetallic inclusions, so, we looked at and because of the highly oxidizing nature of aluminum silicon and we end up forming aluminum oxide and silicon oxide inclusions even before the austenite solidification.

So, once the aluminum silicon solidification the oxidation happens then subsequently the formation of aluminum oxide and silicon oxide attracts the other alloying elements such as the manganese and sulphur epitaxially in reaching the surface of these oxides and leading to the formation of very complex nonmetallic inclusions. And so once you have a formation of inclusion it can be you know made into our own benefit.

For example as I already explained the inclusions are also acts as a potential nucleation sites for when the nucleation of acicular ferrite. So, if you favorably modify the size and volume fractions and you may also improve the mechanical properties of the welds by nucleating or settle for it and subsequently when you form austenite in the weldments upon solidification. And if you form very bulk large inclusions of the nonmetallic inclusions you would expect the nonmetal property weld metal property deteriorate significantly.

So, therefore it is very important to control the environment especially the presence, the presence of oxygen during welding and if use energy GMAW, the use of a proper shielding gas as well as the atmosphere protection of the liquid melt it is extremely critical in controlling the size and volume fraction of these inclusions. And we also looked at the partitioning effect of aluminum to delta ferrite so when you have an in the in the order of 111.18 weight percent in steel and so the aluminum in this partition to solidifying delta ferrite.

Whereas all other alloying elements would tend to segregate towards liquid, aluminum has an affinity for delta ferrite and segregates delta ferrite instead of going to liquid. So, if you enrich delta ferrite in aluminum and if the aluminum concentration goes beyond critical limit the thermodynamically delta ferrite cannot transform to austenite and upon subsequent cooling. So, we end up stabilizing Delta ferrite at the fusion boundary when the solidification begins when by a nucleating the delta ferrite at the aluminum partition towards delta ferrite and thereby stabilizing the delta ferrite to the fusion boundary.

If width of these delta ferrite zone at the fusion boundaries as a function of again the thermal gradients as well as a cooling rate that is actually prevailing in the, during welding and generally the gas metal arc welding GMAW welding delta ferrite layer is like more. And unless beam welding and in an resistance spot welding these delta ferrite layers decrease significantly because of a very steep temperature gradient.

And there is not much time for aluminum to partition to stabilize delta ferrite. So, these are the important roles of, role the silicon aluminum plane. We will move on to the other alloying elements which are present in the advanced high strength steels which are actually commonly there. For example, carbon, so what does carbon do during welding? And we look at the effect of carbon during solidification.

And the other alloying elements which are considered detrimental for welding, for example phosphorus, so you already learned that phosphorus is also added in some of the advance high strength Steels especially to stabilize retained austenite Phosphorus can also be used to and a certain limit, because phosphorus also has an effect on cementite destabilization.

It also destabilizes the cementite similar to what a silicon aluminum does and phosphorus also very effective solidification center. And so for a steelmaking point of view to generate microstructure phosphorus can be used to certain extent but phosphorus is extremely bad considering when you consider the welding and because phosphorus segregates to the line boundaries enter into big boundaries during solidification and we will see how these segregation happens and how we can avoid the detrimental segregation of phosphorus in this class, okay.

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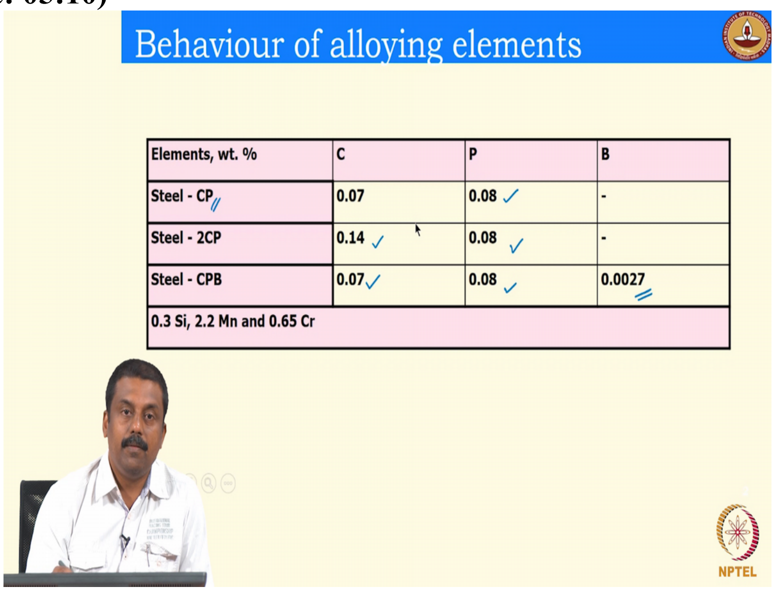

So, if you look at the conventional like chemistry as I explained it we can make varying amount of carbon ranging from say 0.05 to 0.2 there about. And so I am going to show you an example of three cases where the effect of carbon and phosphorous during welding can be seen significantly and understand the behavior of these elements during welding. So, if we consider an example case in advance Iron and steels where we have three chemistries.

Say for example of steel one which is one of Steel CP so it has a common concentrate from 0.07 and the phosphorus of 0.08. And in the second case 2CP where we have a double amount of carbon okay and the phosphorus being the same. And in the third conditions, so we will see these the carbon concentration similar to what you have it in the first case steel CP and phosphorus is same but we added some amount of Boron because we have also seen in the previous lectures.

Boron is also added in some Steels to increase hardnability especially in non stamping Steels boron is very, very much preferred. Not a kink is hardnability but boron can also play significant role in grain boundary diffusion of the allowing elements. How, we will see in subsequent slides so if you can the example what I am going to show you is in a welding behavior of three steels phosphorus of 0.08 and still 2CP we have doubled the amount of carbon and all other alloying elements are same.

And steel CPB and we have a carbon concentration similar to CP but we added about 30 ppm of boron and we keep the all other alloying elements same in all these three steels. So, by comparing steel CP and 2CP we can clearly see the effect of carbon on the weldability and the properties of the weld by comparing and CP and CP B we can see the effect of boron addition on the weldability okay. So now from these examples we can understand the role of alloying elements clearly during welding, right.

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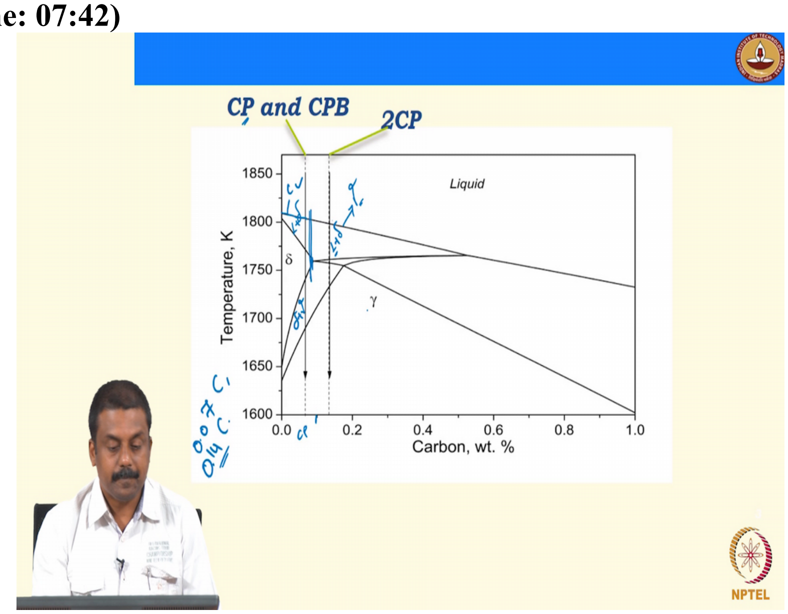

So, we will move on to the first the phase diagram. So, the first understanding, we will have to make when you want to understand the elemental behavior is this solidification mode. How the whirl pool solidifies and when you cool whirl pool to subsequently room temperature right? See the mode of solidification extremely important because that is going to determine the segregation behavior of the alloying elements especially the alloying elements which partitions towards liquid.

So, if you look at the example I showed you the three chemistries and we have two carbon concentrations so one is 0.07 the other one is 0.14 carbon concentrations, right. So, the steel CP if you look at this solidification sequences, of course, you have inclusions already formed, okay. That goes without saying when the liquid is cooled to below solidification temperature and if your carbon concentration is say less than, say for example a peritectic reaction temperature so what will happen?

First in this case we will have a liquid solidifying first into delta ferrite and then because of the low carbon concentration you will have a complete solidification of liquid into a delta ferrite and you will have a single phase Delta ferrite forming; whereas if you increase the carbon concentration and you will first have an liquid solidifying delta ferrite and subsequently the mixture of liquid delta ferrite would transform into an austenite by an a peritectic reaction.

So, the solidification mode have significantly have an effect on the partitioning behavior of carbon. For example if you have an direct solidification delta ferrite and so you are partitioning of carbon to liquid will be maximum because the solubility of carbon in delta ferrite can be much more smaller than the solubility of carbon in austenite. So, when liquid solidifies directly delta ferrite even liquid will be enriched in carbon given by the liquid carbon in liquid line.

Whereas if you have eutectic reactions, obviously, when a liquid solidifies in Delta ferrite first and then subsequently this mixture of liquid ferrite would transform into austenite ferrite. So then, yeah, because of the higher solubility of carbon in austenite your liquids segregate, carbon segregation liquid can be decreases, can be decreased. So the solidification mode has a significant role in the carbon partitioning in the unsolidified liquid in the solidification.

And so when you have an solidification directly to a complete delta ferrite and micro secure becomes 100% delta ferrite and subsequently delta ferrite transforms to austenite and you may expect an a larger segregation of carbon in liquid which is been in during solidification. So, in this case, now we have two chemistries where we have a an 0.07, 0.07 weight percent carbon and then 0.14 carbon. So you would expect that the steel CP now would there completely solidify into Delta ferrite first and then subsequently tougher it will transform to austenite.

Whereas in steel CPB the solidification is directly first will be in Delta ferrite will be nucleating the liquid plus Delta ferrite would transform into austenite by a peritectic reaction and subsequently you know liquid and austenite will have an equilibrium, when a peritectic reaction completes.

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And we will see the solidification behavior of whirlpool using an high temperature camera where we can understand very clearly at the solidification mode of a whirl pool. So I am going to show you in a video and so where the actual solidification microscopes revolution was captured using a high temperature camera which is known as laser confocal microscopy where we imposed a weld thermal cycle onto an liquid pool and we are under we observed the solidification behavior of an whirl pool with the chemistry similar to an, in a dual phase steel chemistry.

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So what you see in this video is the first thing you notice is this guy so that was actually an inclusion. So I will go back again. So, so these guys nobody see over here so that is the inclusion and inclusion has formed already even before the solidification has begun and what you see over here? This is your heat affected zone and this is your fusion boundary. So moment you have solidification, so you will have first delta ferrite nucleating and it is going from the fusion boundary towards liquid.

And what you see over here the reaction is the peritectic reaction. So you will go back here. So you have an delta ferrite nucleating and we have an eutectic solidification going towards the weld centre line and then moment you have an sufficient under cooling, you will have a delta ferrite and liquid interface transforming into austenite. Now the liquid will be going will be solidifying directly into austenite after the peritectic reaction.

So now with the important things you need to all understand here in this solidification is so when I have an solidification begin so how the alloying elements partitioned to these the boundaries of the grinds when you are solidifying and subsequently how the carbon is also pushed towards the untransformed liquid and because the carbon concentration of liquid is always higher than the solidifying products.

The carbon would tend to segregate towards the unsolidified liquid thereby enriching the liquid during solidification. So, if you look at it in this solidification mechanism so you will have an partitioning of carbon to the un-solidified regions at the interdentric boundaries as well as liquid is modifying at last. So now we will see in a simulation.

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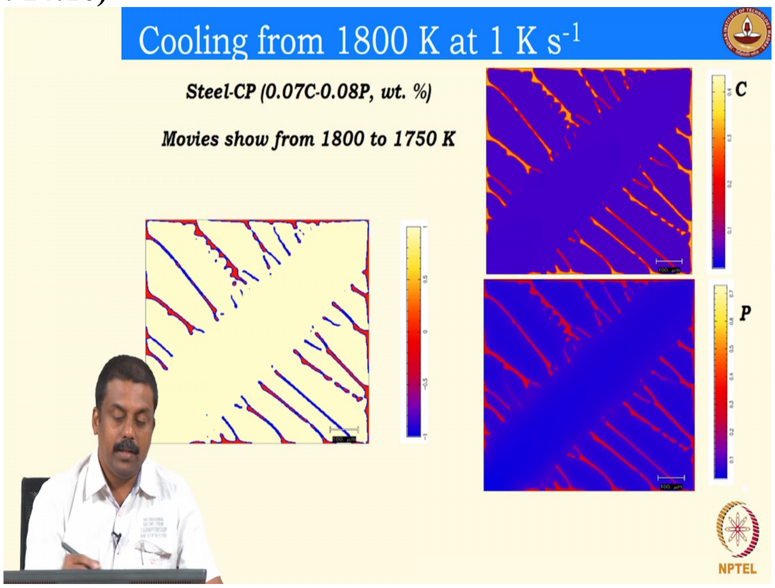

So, we can also understand how these alloying elements partition during the solidification by an simple calculation. So, if you look at it and this slide shows the computer simulations of solidification process what I showed you in real life, so in this video. And we can also create in computer the solidification of dendrite. What you see over here is the actual micro structure where you have a, initially to begin with, you have a liquid which is red in color and we have when delta ferrite and it delta ferrite is solidifying for a steel CP where we have a solidification is first to completely solidifying into delta ferrite and then subsequently delta ferrite will transform into austenite upon sub further cooling.

And during this process we can also simulate the partitioning of carbon. For example and phosphorous and understand how the carbon atoms migrate from the delta ferrite region to unsolidified liquid. So here we can already see here. Now we begin with the carbon concentration of 0.07. But when the solidification is progressing carbon migrates to the unsolidified liquid and thereby the carbon concentration gets enriched in the liquid which is not solidified.

And subsequently the carbon concentration at the dentric boundaries, when it develops and these regions common carbon concentration can go as I as even 0.4. So, even though you have a bulk carbon concentration of 0.07 and because of the carbon partitioning during solidification and lead to a severe enrichment of carbon atoms in the un-solidified liquid in there by the grain boundaries are genetic boundaries in this case, getting enbrittled. And the behavior can also be observed for phosphorus as well I guess as phosphorus also segregates in the similar way of carbon.

And even though we have in a very small amount of phosphorus 0.08, you may still see a severe phosphorus segregation at the interdentric regions and as well as the regions which solidify at the end. So, if for a bulk a phosphorus concentration in the liquid of 0.08 you may end up having enrichment at the genetic boundaries close to the level of 0.7. So, that means know that in this solidification behavior as well.

So, if you look at it now you would end up having a segregation at the interdentric boundaries as well as the when the regions which are solidifying at the end in carbon and phosphorous and the tune of .4 to .7 respectively. So, that means that you know even if you start with in a very low amount of carbon and phosphorous liquid which is a bulk carbon concentration and bulk phosphorus concentration.

And locally at the grain boundaries interdentric boundaries and the weld centerline you may expect and a very strong segregation of carbon and phosphorous and you all know that if you have a 0.7% of phosphorus and you have an extremely brittle grain boundary and as well as carbon as well. So, now we will see a steel CP again in steel CP’s case. And so first we have the complete solidification of liquid into Delta ferrite and then subsequently delta ferrite transforms to austenite.

And you may expect and a very serious segregation in this case because Delta ferrite carbon concentration is much less than liquid carbon concentration, there will be severe partitioning of carbon from Delta ferrite to liquid when it is solidifying.

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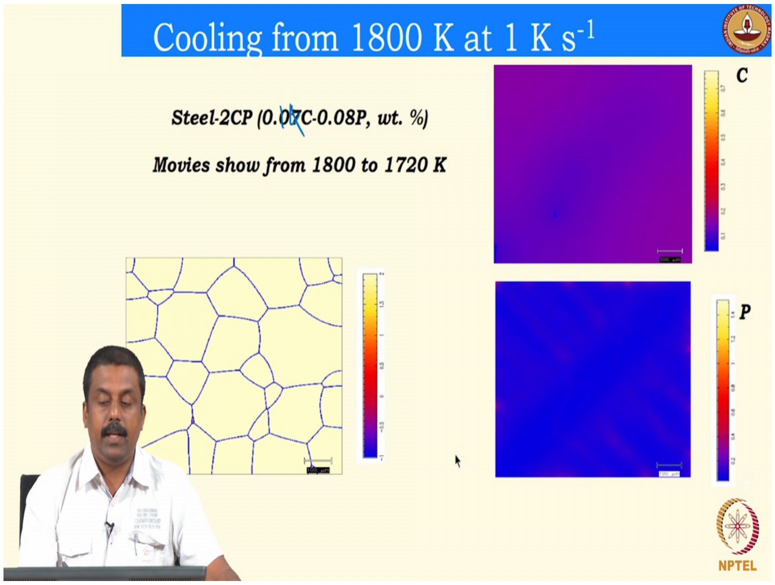

Whereas in the steel CPU has been explained still CP we still have 2CP where we have 0.14 a carbon concentration and you expect an peritectic reaction ad then because of peritectic reaction you may expect locally the carbon concentration changes. So, in this solid, in this move as steel the solidification mode which first is you are having a liquid plus the Delta ferrite and then subsequently this would transform into the austenite even when you have a liquid in the material.

Similarly you know you can understand the segregation behavior. So you have a now double the amount of carbon concentration in the bulk. So, with that bulk carbon concentration you may still expect a segregation of 0.7 and the phosphorus up to say much higher than you see in a steel CP so then this is very bad right. So, the carbon partitioning and the phosphorus the weld center line and the grain boundaries would make the grain boundaries very brittle and can lead to an embrittlement.

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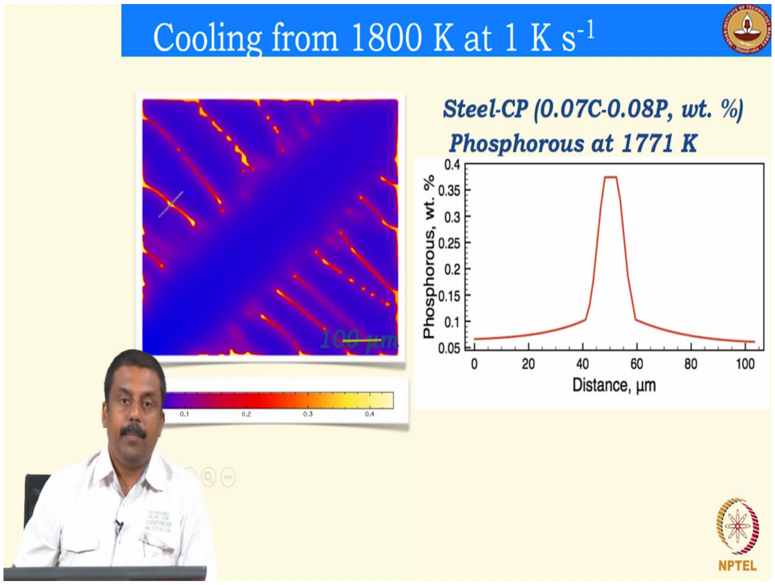

And we will see in the subsequent slides and how this embrittlement can lead to the deterioration in the mechanical properties. And now we will compare in one case where so we if we froze the microstructure at a temperature about 1771 Kelvin. So, the solidification begins somewhere about 800 Kelvin. And we froze the microstructure at 1771 Kelvin and we will see at one point where we have still liquid is present on these regions for example, at this boundaries.

And if you look at the phosphorus concentration variation along this line, so along this line if you look at the phosphorus concentration variation and you can see that and locally the phosphorus can go up to 0.4 you know 0.4 % that is what I explained in previous slide. And this is due to the partitioning of phosphorus from the delta ferrite towards solidifying liquid, right. So you so to begin with, the liquid, all the liquids has the phosphorus concentration of 0.08.

And because of the partitioning of phosphorus from the liquid to the solidifying a liquid and lean can lead to the enrichment of phosphorus at the last solidifying liquid regions and that these regions can be enriched in phosphorus, for example in this case, the phosphorus concentration at these boundaries can go as high as 0.4 weight percent.

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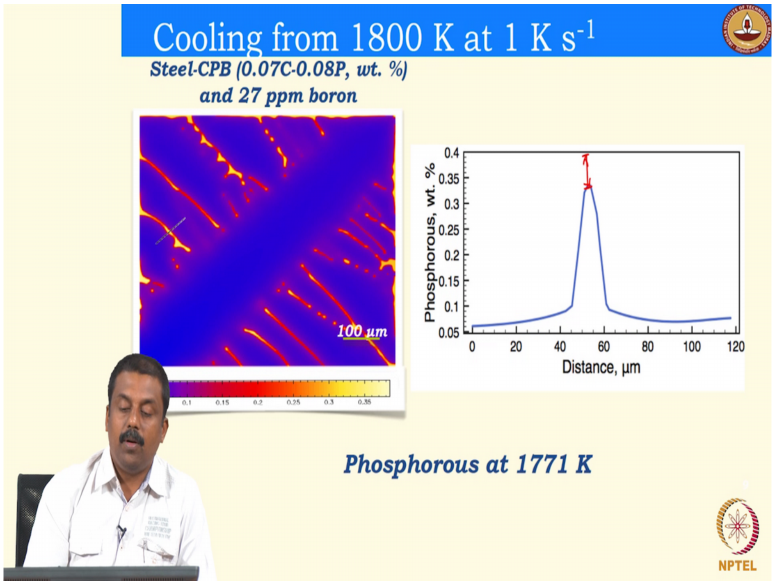

So, now, what happens? Now if you look at the steel with an 80 ppm of boron sorry 30 ppm of boron. So, what boron does? Boron do? So, what we see that this is in a steel CPB where we have a 30 ppm of boron. So, what happens with the presence of the 20 ppm of boron and we have already seen that in the amount of phosphorus at the interdentric boundaries decrease some amount. So, previously without boron you see that phosphorus concentration can go up to 0. close to 0.4 whereas by adding 30 ppm of boron the phosphorus at the interdentric boundaries is already decreasing to about 0.1%.

So, now what does it mean then? So that addition of boron is favourably reducing the segregation of phosphorus and interdentric boundaries and the boron atoms once it segregate. At the solid liquid interface and it stops the phosphorous atom to coming to the boundaries. The boron diffusion of boron is much, much rapid than phosphorus. So boron atom can readily diffuse from the delta ferrite to the boundaries of solid liquid.

And then once you have the segregation of boron at the boundaries, it subsequently stops the phosphorus atom coming to the boundaries. So, therefore the by adding boron can positively influence the segregation behavior to our favor where it can reduce the phosphorus segregation at the solid liquid interface and they subsequently and the grain boundaries segregation of phosphorus can be decreased significantly.

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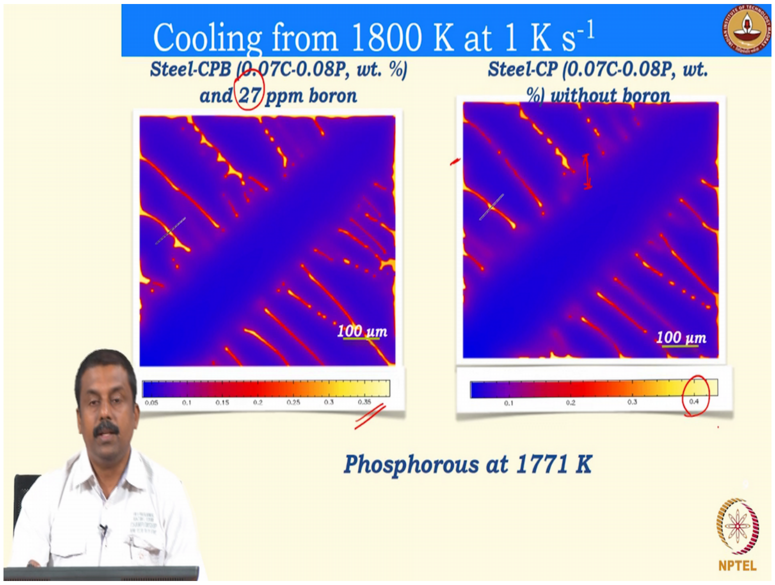

So, this can be seen for example comparing these two. So you can already see this steel with 27 ppm at 30 ppm of boron the maximum possible segregation is 0.35 at one point whereas you would expect higher phosphorous aggregation and without boron. So, boron is already effectively fairer will be modifying the phosphorous aggregation. And it can lead to a change in mechanical properties because once you have reduced the phosphorous aggregation at the grain boundaries then you may already introduced the brittleness of the microstructure.

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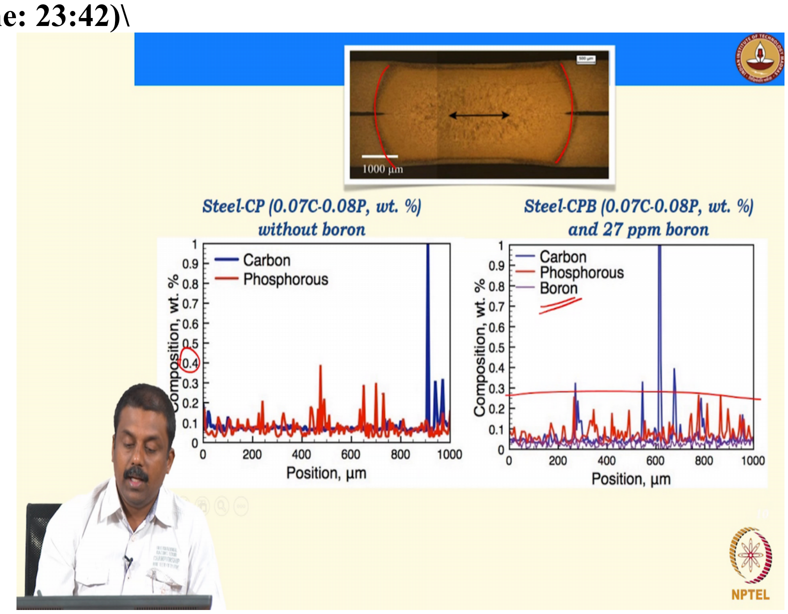

So, you see the some scans to confirm what I showed you. So, if you have only carbon and phosphorous without any boron, you see the segregation this is a measurement carried out on a real weld. So, this is in a spot weld what do you see over here so this is your weld nugget what you see here and then the, when you look at to the elemental mapping along the center line the black arrow, what is seen over here and you would see the local the interdentric regions, the phosphorus segregation can be seen as sis 0.4 as I showed you in the calculations in the video.

Even steel with the boron with the 30 ppm of boron you already see the red the phosphorus concentration can decrease already even less than 0.3 at locally. So, even much less than 0.3 you can see so the boron is indeed effectively reduce the phosphorus segregation. So, we can play around now with the chemistries to avoid the formation of the little brittle grain boundaries.

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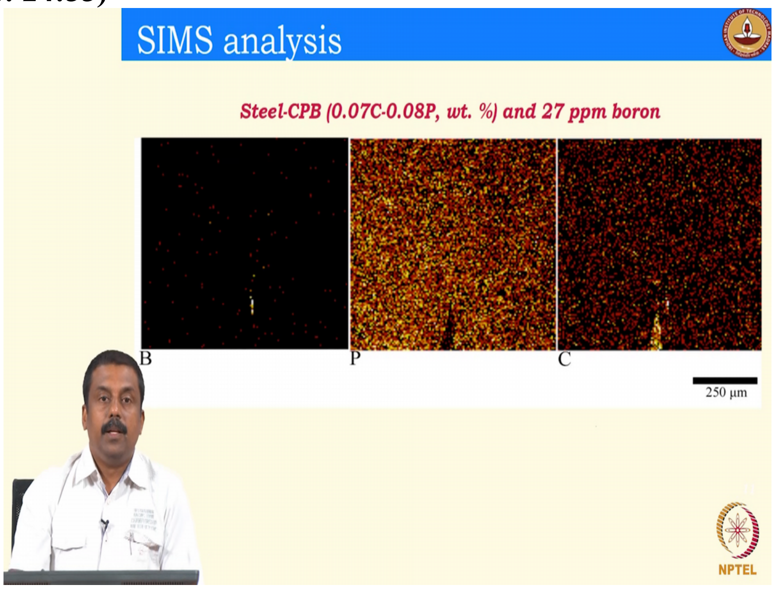

So, you can also see the same the measurements observations using an secondary iron mass spectroscopy where you can see the elemental distribution clearly. So, if you look at the notes at center line you see in a one-point boron segregation, so once you have an boron segregation and the location and you see an a depletion of phosphorus concentration. And that locations close to where you see boron segregation.

So, that means that you know boron indeed stops the phosphorus atoms coming to the unsolidified liquid thereby the phosphorus induce the grain boundary embrittlement can be avoided.

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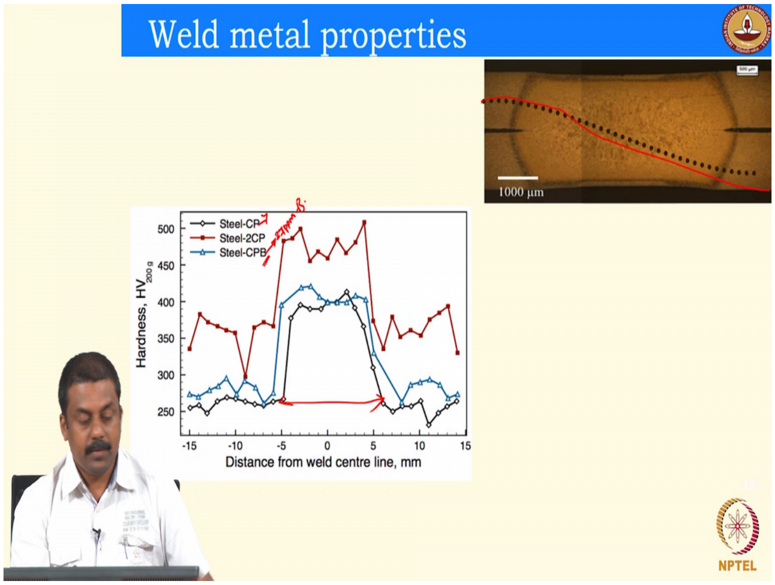

So, you will see the comparison between the hardness of the welds and if you look at it because you know I am comparing the steel CPA and CPB and we have the similar carbon concentration, of phosphorus concentration, the only difference what we have is a CPB is about 27 ppm of boron, right. And see at the boron additions, you know, may influence the formation of the martensitic transformation and subsequently in cooling to room temperatures but you would not see much significant change in the hardness values.

So, what you see over here is the hardness variation over the length of resistance spot weld nugget. What is show here is the top image of the how the hardness variation happens when you move from one side of the base material to the other side of the base material. You see the weld has been a significantly increasing in hardness and because of the formation of complete martensitic microstructure and comparing two steels like for example, steel CP and 2CP and we have a double the amount of carbon concentration.

And that can lead to an a significant increase in the hardness of the microstructure because the carbon is also very effective solidification strengthener and you may also have martensitic microstructure which in carbon compared to CP and you may expect an increasing hardness that is what you see over here and whereas in steel CP and CPB you and you do not see much variation in carbon concentration because the all other composition of the alloying elements are the same except boron.

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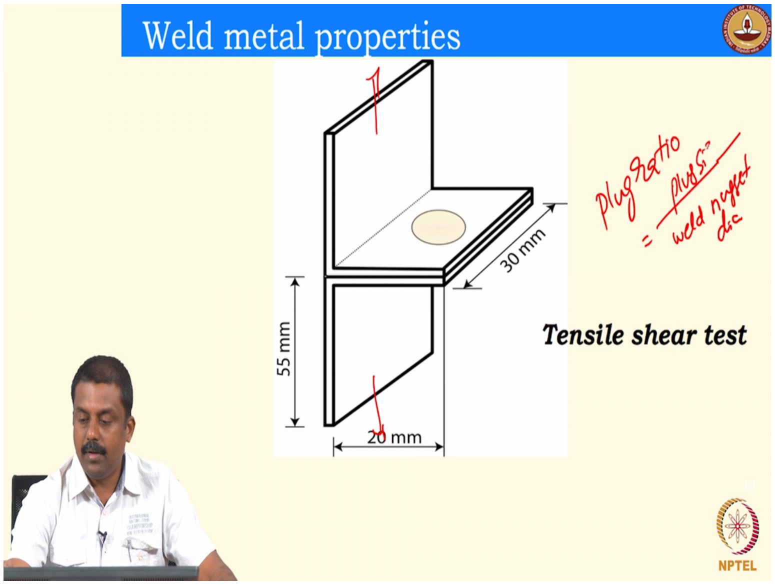

So, we look at now the mechanical properties of the welds of these three cases and we carried out the tensile shear test. And I already explained how we carry out this test in the during resistant spot welding lecture. So, basically we make a weld nugget in a L flanges and then we pull it in metal tensile load and observe the load of failure as well as the plug ratio. So recall what is plug ratio right? So plug ratio is weld nugget diameter over the plug size after failure.

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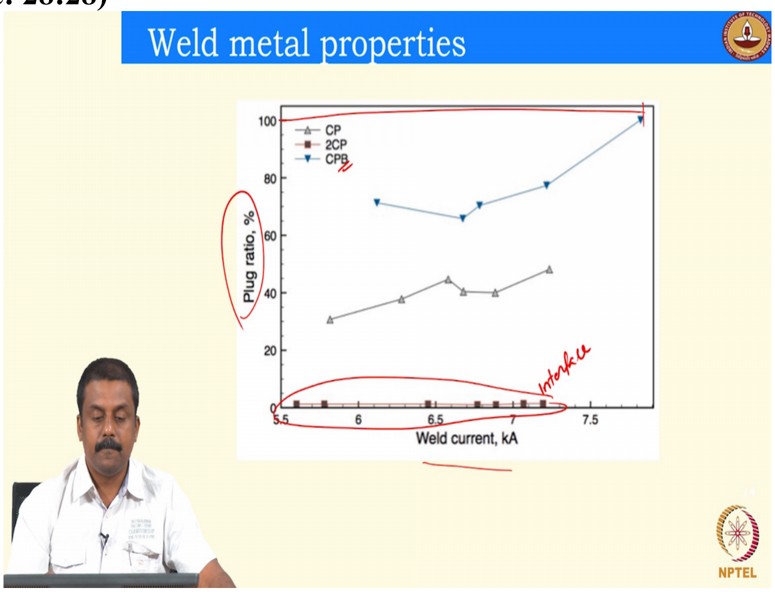

So, you see already the steel CPB have very good plug ratio. So, if plug ratio is close to 100 that means that you have a complete plug failure. And if your plug ratio is 0 then what happens and then it has a complete interface failure right. That is what I explained in the previous resistance part in lecture. You see so we see as a function of welding current not the Imax the maximum current.

You would see that you know complete plug failure is observed for a steel with boron and that if you have boron whereas steel stoop and CP has an mixed mode failure and where a failure plug ratio is not really acceptable whereas in CPB as an a very good acceptable failure mode. But it to steel 2CP maybe you see that no there is no plug at all left. So, you can imagine that you know the failure will be completely the interface failure.

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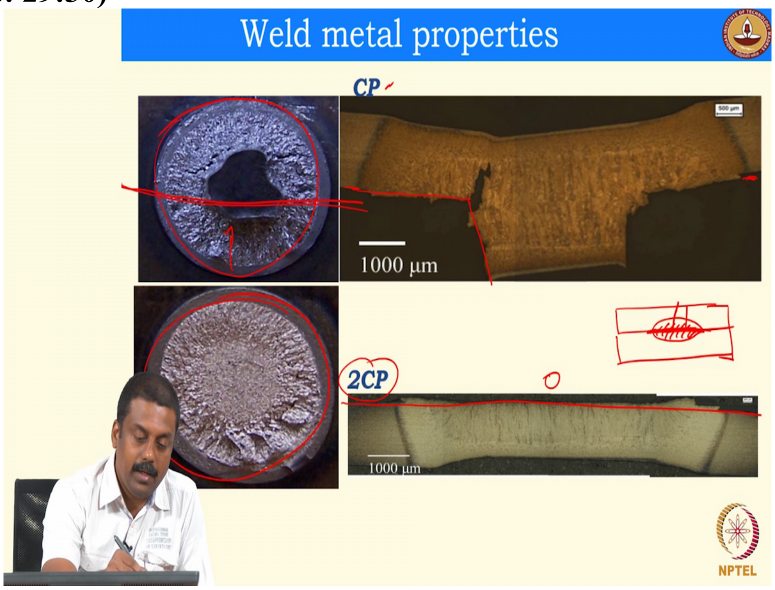

So, this is what happens when you look at the plug sizes. So, in steel CP the failure is in a partial plug failure. So, where we have the what you see over here is weld nugget diameter you see over here and then if you look at the cross sectional view so if we take a cross-section somewhere over here and then I look at from this direction, what you see over here is then steel CP, the crack happened, the crack formed at the interface, the prior interface before welding and then propagated along the weld centre line and then failure happens the ones in the middle of the weld nugget.

The same from other side starting from the weld centerline, the preview crack is created from the prior interface. So pre interface how does it look like? So, if this is your weld nugget along the cross-section so when you make cross section along this plane, so along this line for example and if it looks like this, so it is your prior interface and this is your weld nugget crack nucleated from this location and propagated along the weld centre line and then failed.

So leading to an partial plug failure and this is a very typical behavior when you have an weld center line solidification. So, this centre line is the last solidifying region in resistance spot welding obviously you will have segregation of phosphorus and carbon along this weld centre line so when you have an a brittle weld centre line so when you test it you know in a tensile shear testing as I explained in previous graph.

So you have a crack nucleated and following weld center line and subsequently failing along the weld centre line leading to the partial interface failure. And if you have very severe segregation along the weld centre line and you will have a complete interface failure okay where you open up the welded plates as it was before welding. So, that means that there is no weld nugget remains on the weld region and you will have a complete interface failure.

And when you have a very strong segregation obviously in 2CP's case and the carbon concentration is very high and you segregate weld centre line completely with carbon because that is region which solidifies at the end and that can lead to a complete interface failure where the plug ratio registered here it is zero. So, because there is no plug remaining in the weld and here we see some plug remained and but it is not still acceptable.

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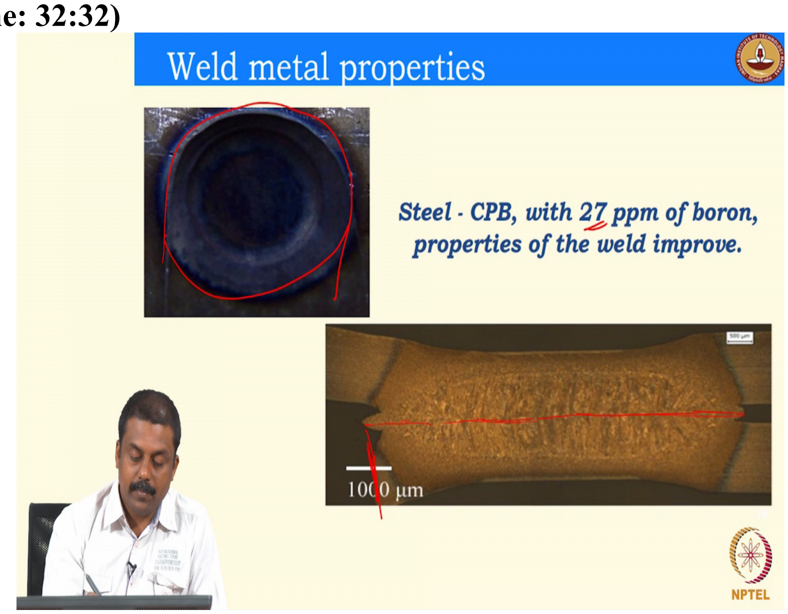

The acceptable case is the case here where we had at the 30 ppm of boron 20 ppm on boron and you see the failure is completely in the heat affected zone elsewhere. And if you look at it and the entire spot weld nugget is remain attached as it was before a tensile. So, that means that I know the; with the addition of boron the centerline segregation of phosphorus is minimized.

And so when you have when tensile testing we found that the crack is actually formed along this edge and then propagated in the heat of weld zone itself. That means that weld is weld properties are even better than your best material property. And that this happens because we managed to avoid the phosphorus segregation and along the center line and by adding the boron and that can lead to improvement in the mechanical properties of the weld.

So, therefore in addition of boron we can say that you know the phosphorus segregations reduced at the weld center line and leading to an improvement in their mechanical properties.

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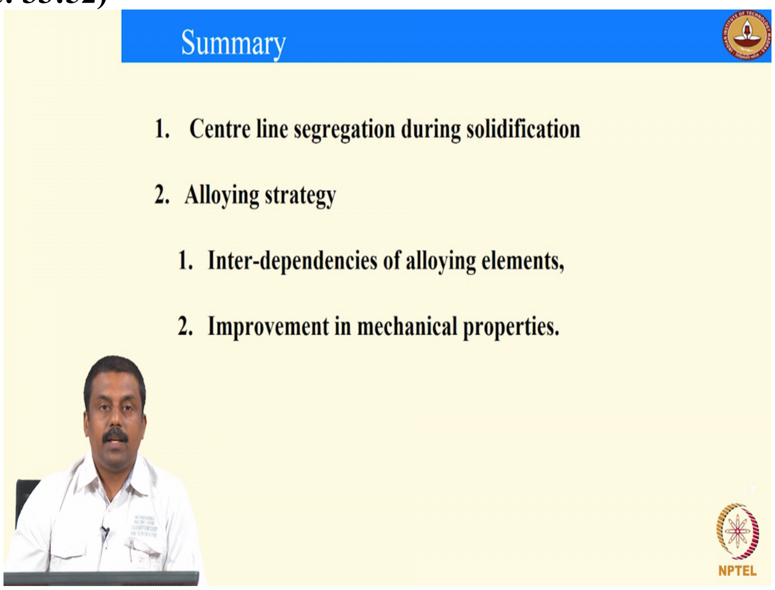

So, to summarize so we looked at the center line segregation of the alloying elements mainly carbon and phosphorous and why they are detrimental during welding and it is important to understand the solidification mode of these steels based on the carbon concentration if you have a low carbon you may expect a complete delta solidification subsequently delta ferrite can transform into austenite and this can lead to a segregation of a liquid carbon in liquid.

And so any of peritectic reactions obviously we may also have austenite forming from liquid to plus Delta ferrite mixture. And you may also locally change the carbon concentration of liquid because of these reaction and we looked at an solidification microstructure institute and during solidification how the dendrites are evolved and how the solidification progress. And we come; we looked at the carbon and phosphorous atom migration during solidification via on a computer simulation.

And we also studied about the role of the contemporary contemplating alloying elements. For example, boron so how boron can stop the phosphorus segregation at the weld center line and because of that how the mechanical properties of the welds can be improved significantly in advance high strength steel.