Welding of Advanced High Strength Steels for Automotive Apllications

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Lecture - 20
Methodologies to Improve the Weldability of Advanced High Strength Steels

So, in the early classes we looked at the effect of alloying elements and how the alloying elements segregate during solidification and that can lead to the embrittlement of weld. So we looked at the effect of carbon silicon aluminum as well as the phosphorus aggregation on the grain boundary during solidification of the weld microstructure especially in resistance spot welding it is very significant right. So now when you look at the partitioning and we looked at in a carbon partitioning, capacitors partitioning to the solidifying liquid and the weld center line as well as the weld in the primary solidification grain boundary as well as secondary line boundary.

And that can lead to embrittlement and we looked at the adding the other beneficial alloying elements for example pass in order to control the phosphorous segregation how boron can be very useful because of the if we add boron and boron stops the pass or atoms coming to the inter and the interface between this one liquid under grain boundaries and thereby we can reduce the phosphorus segregation.

And we looked at the results of that the experiments where the boron addition can effectively reduce the phosphorus migration thereby improving mechanical properties. But now that the addition of boron are changing the chemistry, it is not always viable and because that is actually still in development work. So, what happens if you are given a microstructure? If you are given a composition, whether we can modify the weld thermal cycle in such a way that we can avoid this embrittlement problem, can be mitigate the weld welding process in such a way that we can reduce this aggregation of these alloying elements and thereby can we reduce the embrittlement.

I am going to show you if it is possible to do the, to modify the weld thermal cycle as well as to improve the mechanical properties by this modification.

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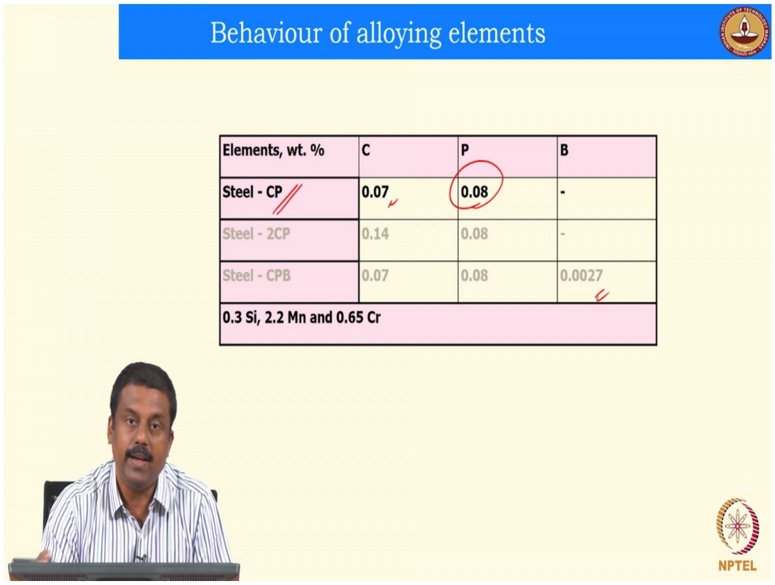

We look at the same example steel what I talked about in our earlier one of my lectures. We have steels of a very low carbon 0.07 with a very increasing very large amount of phosphorous which is not convincingly added. We just added it just to show whether it is possible to generate the advancement of steel with a phosphorous okay. So we looked at the effect of the phosphorus and boron on this segregation behaviour.

And we looked at one case for example one we steel CP we it showed the partial plug failure right so because of the phosphorus segregation. So now we need to say make sure that and this weld of the steel CP does not fail in the weld zone. So we can add first for a boron to avoid the failure of developments at the interface to in order to achieve the full plug failure. But now the steel chemistry is fixed say for example we have only steel CP we cannot add boron.

Can we modify the weld thermal cycle in such a way that we can improve the mechanical properties of steel CP okay, it is possible. We look at one modification weld thermal cycle.

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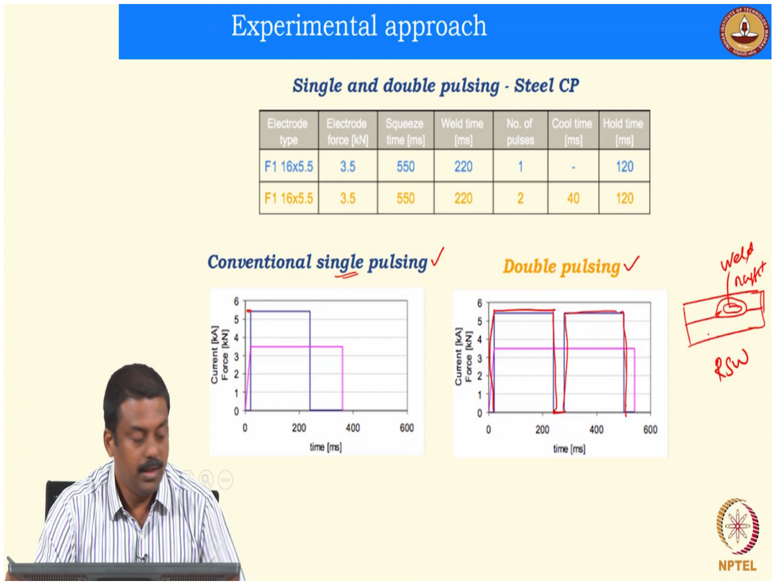

Before that I will explain how these modifications can be carried out. So, this modification we can do that by applying a second pulse during distance part welding. So, in conventional single pulse resistance part welding what we do is again we call our lectures in the resistance spot welding so we have then the current cycle where we give amperage over 5.5 to 6 clamp years.

And we can recall that we can identify the actual current the amperage from the well growth curves we can identify we can apply an amount of load required to keep the failing interfaces and together and then we can play around with the pulsing parameters. And to achieve the varying weld size right. So, now we have instead of doing in a single pulsing in order to avoid in order to reduce the segregation or in order to homogenize the alloying elements in the Weld nugget.

We can also apply in a second pulsing so instead of having only single pulsing, we can also apply a second force pulsing. And whether it is going to improve mechanical properties or not we will see in subsequent slides. Right now we see that in the effect on in the welding parameters to instead of using a single pulsing we do a double pulsing. And in double pulsing what we do is in a single pulsing we have on a single current.

Pulse is given and by giving this pulse and the load and we achieve and weld nugget of say for example so on so diameter we get is weld nugget diameter. Weld nugget, right in the resident spot welding. So now instead of giving a single pulse after an first pulse and we will also apply a second and current pulse as shown over in this figure. And by doing so we may also re-melt it with the first nugget which is formed during first pulsing.

And that can line influence favorably the alloying elements which are actually segregating at the weld centerline. Then we will see in, in the subsequent slides how we can do that.

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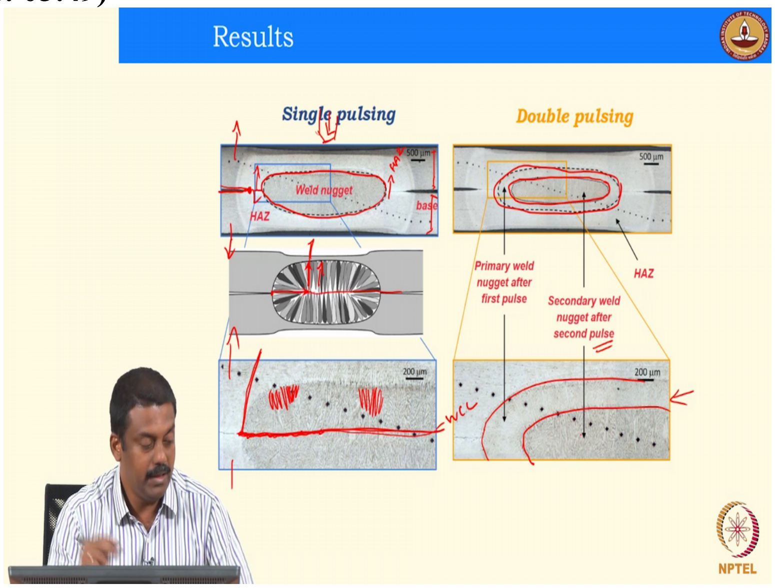

So, what happens in single pulsing? So single pulsing we generate an weld nugget. So, this is sheet 1 is the top sheet and this is the bottom sheet and so when you are applying and using an electrode you pass a current and we also apply a load. And doing so we melt the interface and form already known as weld nugget right and these regions are the heat affected zone regions and during this puss per single pulsing what happens is this is a weld nugget and this is HAZ what do you see over here and this is a base material.

And if you look at in a somewhat higher magnification, you see very clearly the columnar grains which are actually grown from the fusion boundary towards the weld central line and during this process the alloying elements are trying to segregate at the weld center line because that is the region which solidifies at the last, right. So when the grains were solidifying from this direction you will have a segregation are developed a line because of the solidification of this liquid over here it takes place at the end.

And the alloying elements has just caught when phosphorus would be migrating towards the weld center line when the solidification happens from the fusion boundary, okay. So now if you apply load to this microstructure so when you are doing an cross tension test for example when you pull apart these two regions so what will happen so this is the region where you expect a failure, crack a nucleate because that is the interface which is there and you also see this interface is like in a notch, is it not?

So, this interface locked act as a notch and then there will be a stress concentration here at this point when you are pulling along in a tensile direction along this as shown in this figure. And obviously you will have stress concentration and then you will have a crack propagating along this weld centre line and then if because of the brittle elements that are segregated at the weld center line and you will have a crack propagation and then if you have a high amount of segregation you will have a complete inter-phase failure.

So, if segregation is minimal or if you do not have any determined element like carbon phosphorus then you may end up having cracks going like this because this microstructure over here is very strong right, this microstructure here? And you will end up fracturing at the heat affected zone that is very good okay but because of this aggregation of alloying element on the well center line. Most likely if you have phosphorus aggregation and you will have a crack propagating from at the tip of the fusion boundary and going towards the weld center line.

Say for example you expect a crack to happen nucleate at this region and propagate and then moment it reaches a critical limit and because of very strong segregation you will have a failure of the plug okay, whether it is partial and if you have a high segregation you will have a complete inter-phase failure where we have a plug ratio of zero okay. So, now what happens to these singles double pulsing.

In double pulsing, what we do is we also have an additional pulse current pulse is given up apart from these the first pulsing which is actually used to make the weld nugget, right. The second pulsing so this is the first pulse and you would view the first pulse area so what you have over here and this is the first pulsing and because of the second pulse the current you are given you re-melt the sum of the regions inside the first pulse and the nugget which is created by the first pulse.

So, this is the primary weld nugget and this is the secondary weld nugget which is formed after the second pulsing. This is clearly seen from on this image where we have this primary weld nugget which is formed from the first pulsing and then after applying a second pulsing you will have a second melting of the weld this weld center and then you have a secondary weld nugget that is formed after the second pulsing.

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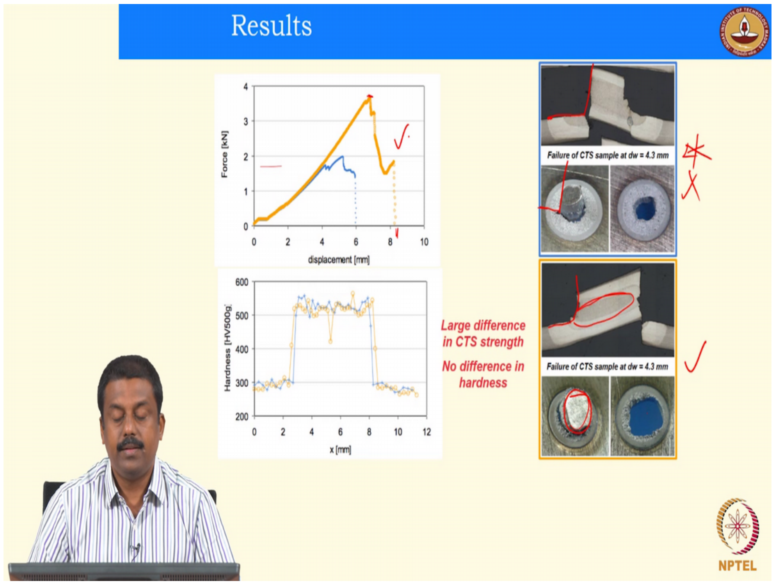

And this can be beneficial and because of the basically what you do we here is big applying second pulsing; you do a heat treatment, okay. You do a heat treatment of the weld nuggets which is actually formed by the first pulsing okay. So, you apply a second thermal cycle which can do a homogenization of the region's somewhere over here for example re, because of re-melting you may also have segregation effects reduced in the regions.

We will see in the subsequent slides what happens in chemically and when you are applying in a second pulsing. You clearly see in the curves who is where and the mechanical properties certainly improve for example the blue curve here it shows the cross tension tensile stress tensile test results where the first pulsing it shows very poor strength, whereas after applying a second pulsing your strength level increases significantly and also have a high displacement.

That is, mean that means that the mechanical properties improve significantly. So, you will see in the first pulsing case the blue case what is you over here is the fully nucleated at the interface from three from the in the heat of the grid zone and then it propagated along the weld central line and then the failure of the plug happened in a partial plug way, mode. So, the crack propagated and then it failed and then it broken, it has broken down at the middle of the weld nugget.

And this is not an; it is not advisable failure mode because you have a plug fail. And in the second case when you have a double pulsing and you see the strength has increase. And if it not increased that means our mechanic properties are improved significantly. So, if you look at the failure mode so the moment you have a failure initiated and then the regions where you see a boundary between the primary and the secondary weld nugget, boundary between the secondary and the primary weld nugget, so these regions, the moment your crack reaches that region so what happens the crack is deflected.

That means that your weld nugget is intact. Majority the secondary weld nugget is intact. So, you improve the mechanical properties significantly by doing a second pulsing okay. And then, second pulsing increased the plug size as well, so you increase significantly the plug size, the plug is intact you see that the plug has come out intact was 80% of the plug is intact. That means that it is much more acceptable failure mode compared to the single pulsing case.

But there is no significant variation in the hardness in the both the cases in both hardness showed that means that sort of similar hardness variation that means that no mechanic from the hardness wise is there is no problem but we have a significant improvement in the failure mode as well as the mechanical property. That means that second pulsing is beneficial to improve the mechanical properties.

But how it does the second pulsing help in improving mechanical properties that is a big question, right? We need to understand what happens when you apply a second pulsing so for that we again will have to look at the thermal cycles.

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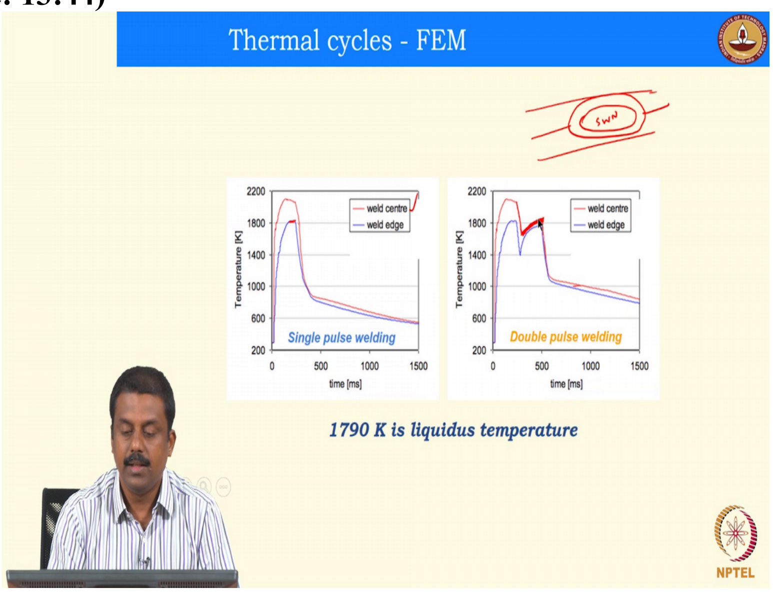

And subsequently how the thermal cycle the change in thermal cycle leading is leading to change in segregation of alloying elements in the in the weld zone during single as well has double pulsing case. So, the first we will begin with the thermal cycle. So, these are all calculated thermal cycle using an FTM simulations. So, if you have a single pulsing what we do is at the weld center so the temperature reaches much above the liquid us temperature and subsequently you cool to room temperature.

And weld center and weld edge based on the peak temperatures you know you may end up having either melting or heat affected zone right. In the weld edge, the melting point is below the peak temperature reached welding reached a below melting point and whereas in weld Center the peak temperature reached is much above melting point. So you will end up having the molten regions between the weld center and the weld edge, okay. In the single pulsing we are not doing any heat treatment.

So, from the peak temperature materials the weld is cooled to room temperature and because of double pulsing and instead of cooling after forming a molten region so you cool it to some temperature and then because of second pulsing the material is again heated up to another temperature and subsequently upon heating up, we cooled to room temperature. So, we modify the thermal cycle I mean from a continuous cooling from weld liquidus temperature and the weld centre upon cooling to or some temperature we will again heat it up like in a post weld heat treatment okay.

So we will again heat it up and subsequently we cool to room temperature. It is the same happens to the weld centre as well as weld edge. The whole thing is in and the weld edge the peak temperature reached in default cycles also lower and will also have an effect of peak temperatures seen very clearly by comparing weld centre and the weld edge okay. So, it is very clear right.

So, in a single pulsing we are cooling continuously from solidification temperature to room temperature whereas in double pulsing instead of cooling to room temperature upon cooling to say some temperature where we have a solid complete solidification and then we increase the temperature to slightly higher. And then subsequently, we cool to room temperature and this increasing temperature can cause a very positive effect by homogenizing the microstructure in and the composition which we already saw in the optical microscopy.

Because of this reheating and this we form secondary weld nugget so this is the first weld nugget and because of the reading we have melting artery in the regions and we form a secondary weld nugget and because of this heating all right.

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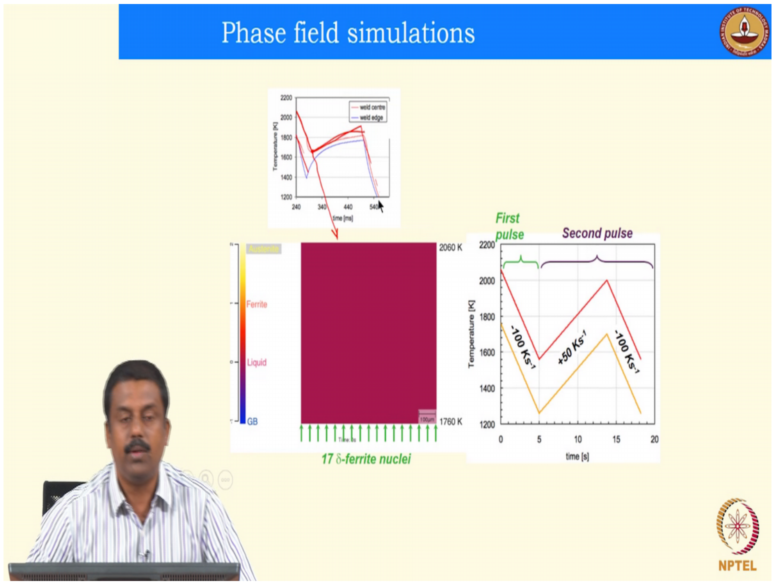

And we looked at the how the alloying elements segregate during this process so we can simulate again and I will show you the; it is also the simulations which we can use it to understand what happens to the alloying elements during this post pulsing or post pulsing heat treatment. So again we look at the in the micro structural evolution, so we have simulated the similar level thermal cycles where we have and both the cases weld center and weld edge we cool to some temperature and subsequently we take it to other temperature.

So in single pulsing case we will continuously cool at the room temperature whereas in double pulsing case so instead of cooling room temperature. We will take it to again to some temperatures and then subsequently cool it back to room temperature okay.

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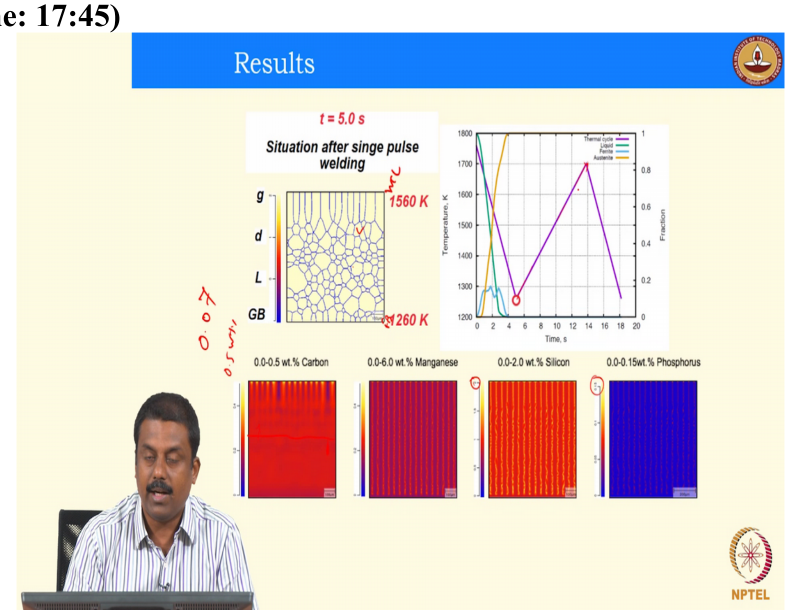

So at time T zero everything is liquid right it is weld center, so everything is liquid over here you see here. And then you will have a uniform distribution of carbon, manganese, silicon, phosphorus in the liquid. It is a single phase liquid right. So when it is liquid all the elements are homogeneously distributed. And then when you start cooling down after the current is positive features of the current, the pulsing is completed.

When we are going to cool down say for example when you reach a temperature of 600 D 600 Kelvin and you have a partial solidification of the Delta ferrite for example in this case we have a delta ferrite as well as the austenite forming okay. And doing this process what happens? Because of the solubility difference between delta ferrite austenite on, in the liquid and you will have a segregation of carbon and phosphorous and phosphorous, manganese, silicon at the interdentric boundaries as well as at the liquid front okay.

So, you will have a segregation based on the solubility of the elements in Delta ferrite and austenite liquid. And you will have a segregation at the interdentric boundaries as well as at the solidification front because that is the region where the carbon atoms are migrating from the Delta ferrite to liquid, okay. And subsequently if you cool further and your solidification is getting completed and you will also have the segregation becomes a very predominant.

For example, in this case, you still have some liquid is left at the weld center line, for example in the simulation shows, this is a fusion boundary and this is weld center line. And you already see that weld centerline the carbon concentration if you begin with 0.07 but the carbon concentration can go up to 0.58 percent.

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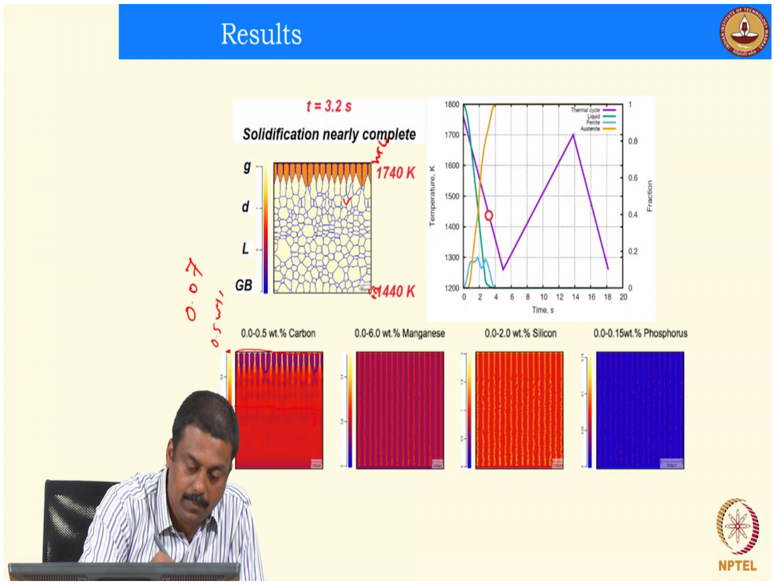

Similarly manganese can go as high as 0.5 and silicon up to 2% and the phosphorous can also go to 0.158 percent okay. And subsequently if you cool down at this point, solidification is completed and you see a significant amount of segregation that weld centerline segregation we always studied right.

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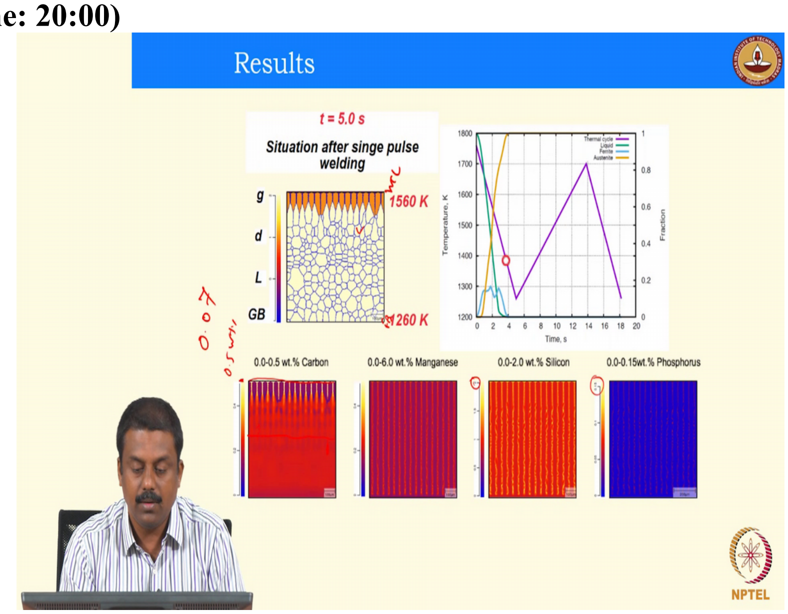

So weld center line is now enriched in carbon the carbon concentration is as high as 0.5 even if you begin with 0.5. So this is the region where we expect an interface failure to happen at the weld centre line. So, now; so in our case we have when a secondary pulse were given second pulse double pulse is given and doing this process instead of cooling room temperature what we will do; so we are now taking again whatever solidified to another temperature okay.

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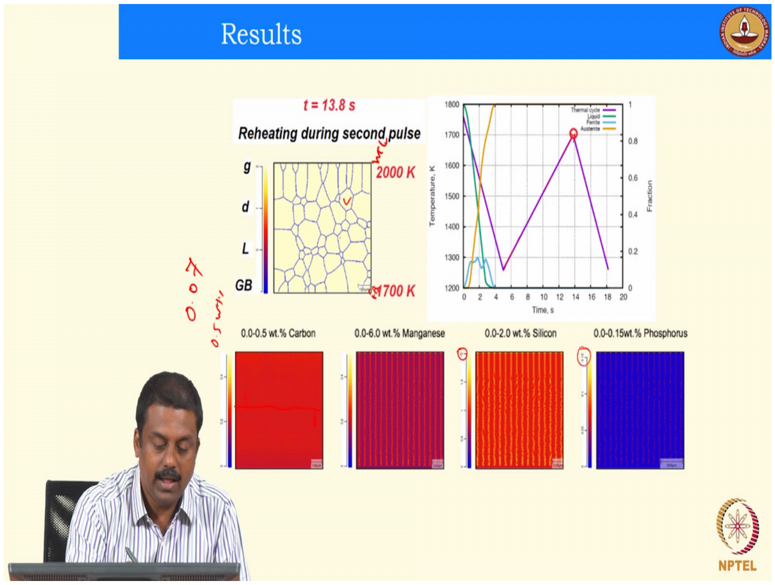

So again we are heating up to another temperature you already see there is a homogenization. You see a homogenization happen from on the weld center line by a carbon and the phosphorus more segregation is really reducing. You can see that in previous graph. For example in this graph you see the carbon concentration is enriching whereas if you heat it up instead of cold solidifying to room temperature cooling to room temperature if you heat it up you see the carbon is already homogenizing okay similarly phosphorus also homogenizing because of the second heating.

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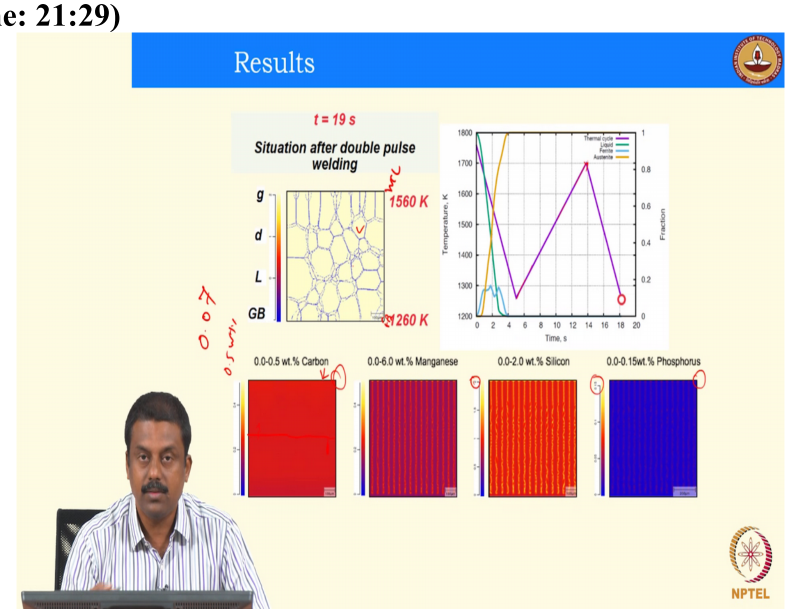

And subsequently if you cool down they will also increase homogenization because still the material is in a very high temperature right. So it will be about a 1300 to 1600 Kelvin temperature.

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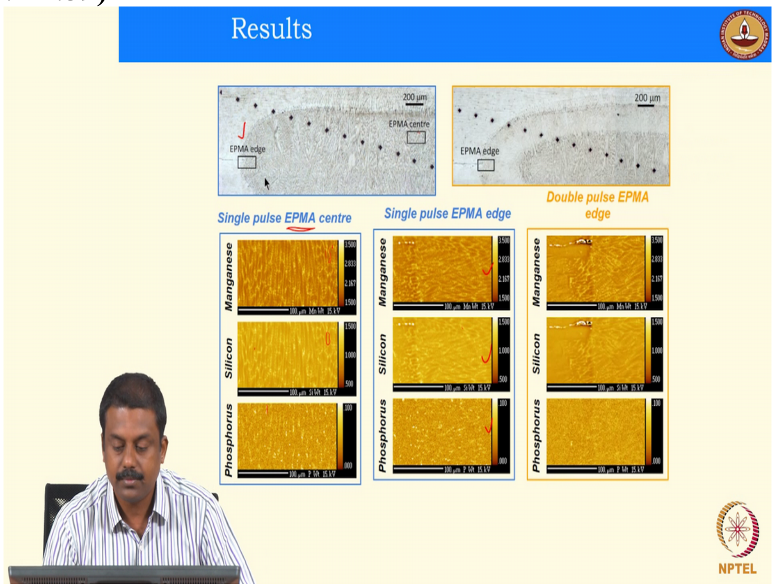

So what do you, what is the result actually we are seeing is that in these only single pulsing in the experimental in these, at also we are seeing it is a segregation of phosphorus, silicon and manganese at the boundaries, interdentric boundaries, you see here in this fiction, you see at the interdentric boundaries the manganese are all enriching. At the boundaries silicon is enriching as well as phosphorus also enriching the grain bound, the solidification boundaries at the center as well as the edge.

And you see the calculation results what I showed in previously is a previous slide also. See the clear segregation of phosphorus and manganese, silicon and manganese at the interdentric boundaries. This is clearly seen also in the experiment by the elemental mapping microanalysis mapping. The same it is actually shown at the edge region and you also see a segregation of manganese silicon and phosphorus at the grain boundaries you see the bright regions they're all segregated regions which are nothing but the interdictory boundaries during solidification.

Surprisingly if you look at the elemental distribution at the edge on regions, at the edge regions after double pulsing, after the second pulse you see already the regions are homogenized. You see that there is no distribution the phosphorus is distributed very homogeneously. Similarly the amount of manganese under weld center line nice here sees a decrease significantly. You see that regions?

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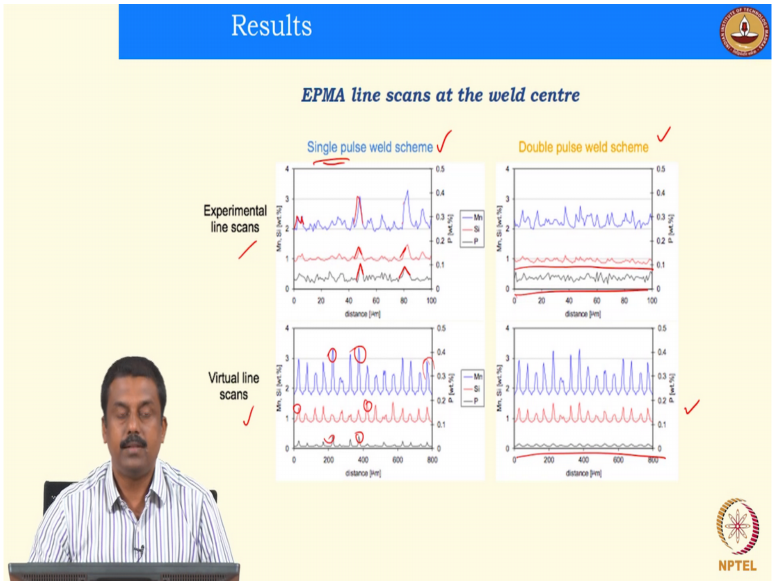

That means that and a double pulsing indeed homogenized is the segregation which actually formed and it will also we can clearly seen from the EPMA line scans at various regions. This is Experimental line scan, during the second pulsing say, for example, line scan is carried out somewhere here somewhere over there, for example, somewhere over here not during single after single and double pulsing.

You see clearly the manganese is segregating in some regions. Those regions are all the boundaries same as silicon is segregating and phosphorus is segregating at the boundaries whereas after double pulsing you see that phosphorus, silicon as well as manganese is more or less the same in almost all the regions that means that the segregated regions are the grain boundaries are all homogenizing.

That is what is also shown from the simulation results and the simulations what is so here is the segregation of manganese, silicon and phosphorus during a single pulsing; whereas in double pulsing you see that and the phosphorus is completely homogenizing after the second pulsing which is the effect is very significantly seen in the phosphorus case. That means that second pulse helps in avoiding the segregation of phosphorus particularly which is actually very beneficial.

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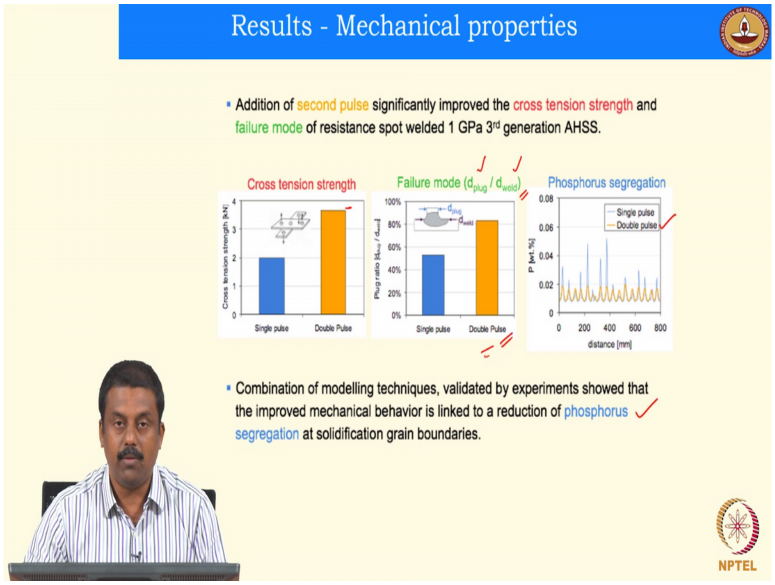

If you do not have phosphorus application and your impediment decreases significantly. And the resource of constants in test we have already shown in the previous slide. After double pulsing the strength is increasing compared to the single pulse case and also the failure mode the plug ratio. What is plug ratio? Again recall from my previous lectures. The plug, the size of the plug after the test testing and the size of the weld nugget, the ratio of that and after the double pulsing, the plug ratio is also increasing significantly, okay.

And that is mainly due to the reduction of phosphorus segregation after double pulsing. So the phosphorus segregation decreases significantly at the grain boundaries and the weld center line leading to the improved mechanical properties. So that means that so you do not need to change the chemistry by carefully manipulating the weld thermal cycle they can still improve the mechanical properties of advanced high strength steel.

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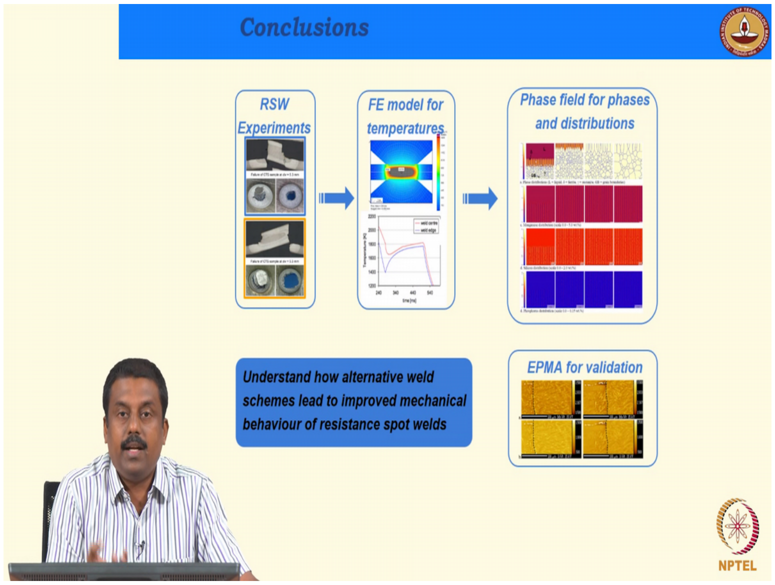

That is the lesson I want to give you and this understanding is possible mainly because of the calculations and the understanding of the elemental behavior during a welding. So, that is the lesson I want to give you for you. Then it is very important to understand the physics behind this process. How this aggregation happens during solidification and once you understand the fundamentals what I explained in this lecture very clearly we can improve the mechanical properties of these welds, either by modifying the alloying elements or by changing the weld thermal cycle.

In this case for example what you have done is we have changed the weld thermal cycle introducing single pulsing, using a double pulsing. Double pulsing leading to homogenization of the alloying elements especially phosphorus and but they are by reducing the embrittlement of weld center line and the boundaries. So, the lesson I want to give you from these lectures is conventionally what we are doing is we do resistance spot welding okay and then you look at the thermal cycle how what thermal cycle is you are going to apply and then the microstructure analyze the microstructure and investigate why the weld is failing.

But now what you have done here is, what you need to understand is now you first to make yourself comfortable with the physics, the metallurgy of these advanced high strength steels during welding.

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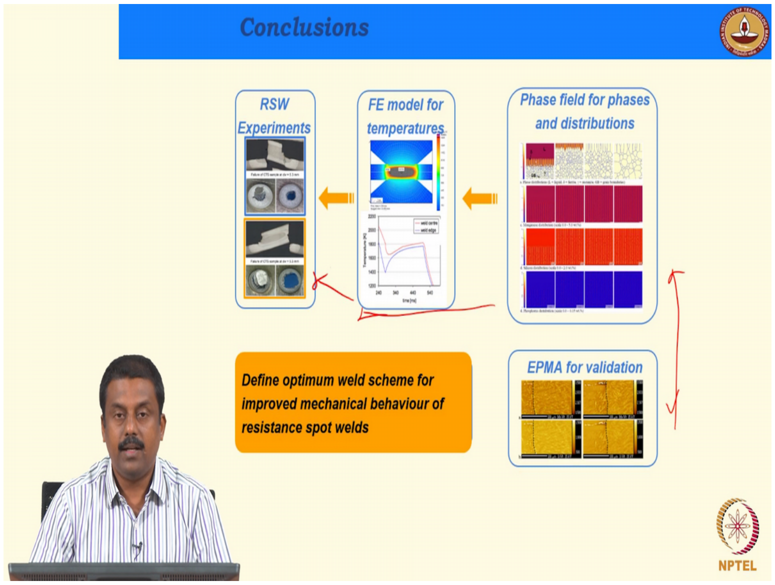

So once you understand that and the instead of playing around with the welding parameters to get the better mechanical properties you know that what mike what microstructure you want, what is application, how homogeneous the mighty elemental distributions would be. And then we can understand the microstructure evolution and which microstructure thermal cycle can give you this homogenization.

And subsequently you can how thermal cycle predicted thermal cycle which can be now predicted to get these microstructures ultimately you are using that thermal cycle best microstructure. So, instead of playing around the weld thermal cycles to get the better mechanical properties and you identify the mechanical properties and the microstructure and the elemental pattern, elemental segregation behavior which can give you the mechanic properties.

Once you know that we can get thermal cycles needed to get you these mechanical properties. So, this is with this way I like to conclude this lecture series so there the lesson I want to give you is it is very important to understand the physics and metallurgy of advanced high strength Steels. By understanding the physical metallurgy and the fundamentals of the alloying elements behaviour and the welding thermal cycles can be identified to weld these Steels.

And we can achieve the best weld from these steels of advanced high strength Steels, by carefully understanding the microstructure evolution and the correlation between the weld thermal cycle and the microstructure.

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I also acknowledge some of my colleagues who actually helped me to generate these results from the metal finish or technology in Netherlands. I will also acknowledge my students who helped me to organize these slides and to help you when you are doing this course through various forums and emails thank you