Welding of Advanced High Strength Steels for Automotive Applications

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Lecture - 15
Welding Metallurgy of Advanced High Strength Steels - Part - I

So, we looked at the overviews of the three important welding processes that are generally used in automotive industry. The first we looked at resistance spot welding and then we moved on to laser beam welding and finally we looked at some of the advances that are so far made in gas metal arc welding which actually you know makes this process very attractive for welding of some of the new generation advance high strength Steels.

Not only welding but also for basic applications. And so, we will move on to the welding metallurgy, the third chapter, how these welding processes affect the carefully designed micro structures of advanced high strength Steels. And we will also look at the effect of alloying elements that we had and what are the behaviors of these alloying elements when we apply a weld thermal cycle.

So, in the in previous lectures I talked about the microstructure of Advance high strength steels and how we stabilize this microstructure by applying a complex heat treatment and adding the alloying elements which are not generally present in the amount we had in the advanced high strength steels in conventional steels.

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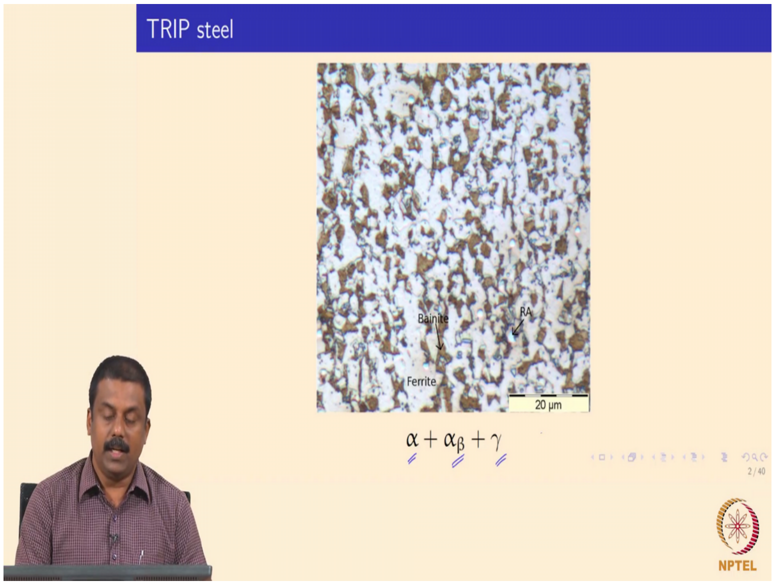

TRIP steel microstructure based material microstructure is given in this slide. So, as we have seen that you know trip steel contains typically three phases: Ferrite, it is a bainitic ferrite and then some amount of retained austenite. So generally this retained austenite gives the superior properties of trip steel when these retained austenite transforms into martensite upon loading, you get enhanced plasticity as well as increasing strength.

And of course these alloying, trip steel also contains the increasing amount of manganese as well as a secant aluminum. They also give a solid solution strengthening. So now, we will see how weld thermal cycle and affect this microstructure, what are the behaviors of the alloying elements during a welding.

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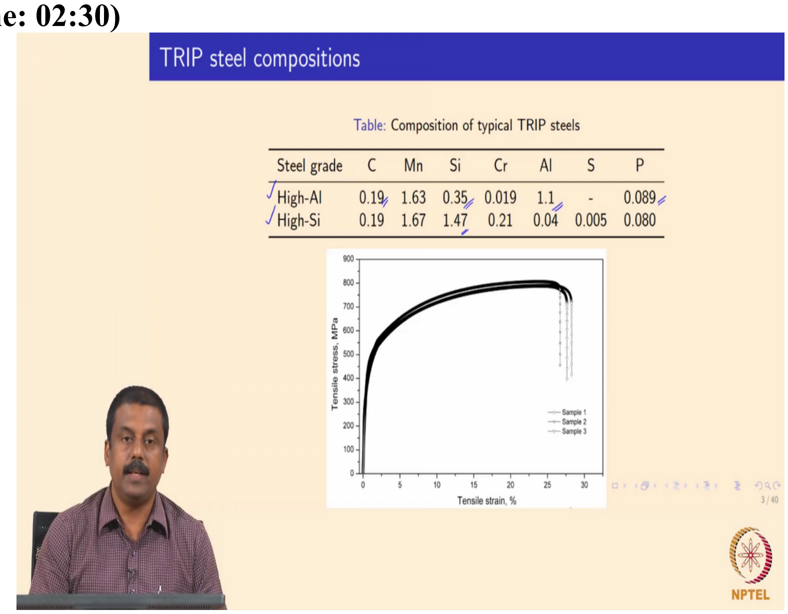

Steel grade	C	Mn	Si	Cr	Al	S	P
High-Al	0.19	1.63	0.35	0.019	1.1	-	0.089
High-Si	0.19	1.67	1.47	0.21	0.04	0.005	0.080

So, as I explained in previous lectures, the trip steel contains the alloying elements of higher amount of either aluminum or silicon or some amount of phosphorus apart from the carbon and manganese. So, until the trip Steels that can be classified into two important grades the conventional trip steels. So, one is the aluminum based trip; the other one is the silicon based trip steel. In aluminum base trip steel we stabilize retained austenite by adding aluminum, aluminum in the range of not more than 1.2.

There is a metallurgical reason why we want to add more than 1.2 that will come to that we will discuss later. But typically it is about 1% aluminum okay. Apart from aluminum we also have about 0.2 % carbon and manganese of 1.5 to say not more than 1.8 in a conventional trip steel. And we reduce silicon in aluminum steel. A silicon is a convincible level in 0.23 to 0.24 and the phosphorus it is kept as a level which is actually considered as a safe in weld, acceptable.

In silicon based script steels we replace aluminum with silicon. The silicon is generally is added in around 1.58% and generally the carbon and manganese remained the same. So there are positives and negative in terms of metallurgical aspects by adding either aluminum or silicon. Silicon based trip seals are conventionally developed and then the commercialization was also started by silicon base trip steels. But there were issues with the addition of silicon because silicon forms on the surface oxides.

So, the galvanizability the became an improper and there was a severe effect of the silicon oxide formation, surface oxide formation and the endurance of a zinc coating onto a surface because of that you know that is from silicon was not seen as a good alternative to generate trip steam. So that the there was some work to replace silicon with the some other alloying elements and the one of the development was to replace silicon with aluminium. And therefore aluminium base trip steel also came into picture.

So, aluminum is also known effective as I already explained and suppressing cemtaite formation. But aluminium is very poor a solid solution strengthener compared to silicon so silicon is a very effective solid solution strengthening in ferrite whereas aluminium solid solution strengthening is not that effective compared to silicon. So the; naturally you know the amount of aluminium is added is sufficient for stabilizing retained austenite but the strength cannot be achieved to higher levels as compared with the silicon based trip steel.

So, the increase amount of phosphorus is also added in aluminium trip steel to compensate these strength, solid solutions strength and loss by the addition of aluminium. And we will see the effect of each individual alloying element during welding in subsequent slides, in subsequent lectures. Right now you can assume that you know you can make a trip steel with two different composition ranges.

So, one is aluminum based trip steel and the other one is silicon based trip steel and aluminium based trip steel may be stabilized with retained austenite by adding about 1% of aluminum and silicon based strip steel we had about 1.5% of silicon to stabilize retained austenite in both Steels. So, even though these steels chemistries are entirely different apart from carbon manganese with the amount of silicon and aluminium percent in these 2 C's are mostly different.

What you have, it is in both the cases similar where we have Ferrite carbide free bainite and or bainitic free ferrite and retained austenite was varying from say 10 to 12% of austenite not more than 15 % because the microstructure rate is more or less similar.

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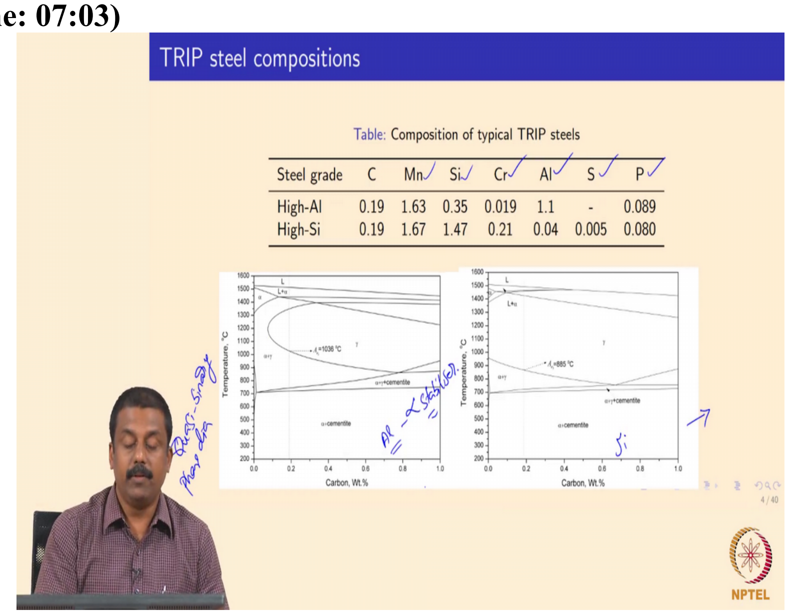

But if you see look at the phase diagrams of these two steels and you see two different entirely at two different phase diagrams. For example, on the left side of the slide you see in an aluminum based trip steel and right side you have an a silicon-based trip steel. So, if you look at the aluminum based trip steel phase diagrams, so these are all the quasi binary phase diagrams, so where you have we plot an iron carbon diagram with an influence of the other alloying elements.

And if you look at by adding 1.1% aluminum so the aluminum being in a very, very strong ferritic stabilizer and we enlarge the delta ferrite loop over here and then now when you have high amount of aluminum your ferrite is delta ferrite stabilized is much lower temperature because the aluminum is very strong the alpha stabilizer.

And this can have a significant influence on the weld microstructure because when you have solidification from the liquid whirl pool to lower temperatures and because of the partitioning of aluminum it can lead to a stabilization of delta ferrite and that can happen in a weld metal. But whereas in the compared to aluminum based trip steel, silicon based trip steel show the conventional iron carbon phase diagram even though he we had at 1.5% of silicon and manganese and the other alloying elements.

The phase diagram looks more or less the phase, the phase fields look similar to in a conventional iron carbon diagram because the silicon is not that effective in promoting any phase it is in very low amount; whereas an aluminum can have a significant effect of enlarging the delta ferrite and austenite loop what we call is the inter critical loop. So, even though the mechanical properties the microstructure may appear similar in terms of the microstructure evolution.

And these two steels when it when they know, when they cooled continuously from the melting point and you may expect an a different stabilization, the microstructure stabilization microevolution mechanism can be entirely different in these two steels because of the change in the phase fields in the in the phase diagram what you see over here in this slide. So, we like to now see in initial cases and if you apply a typical weld thermal cycle and how the microscope evolution takes place even though your base microstructure may appear similar. The Weld microstructure can entirely be different based on its individual composition.

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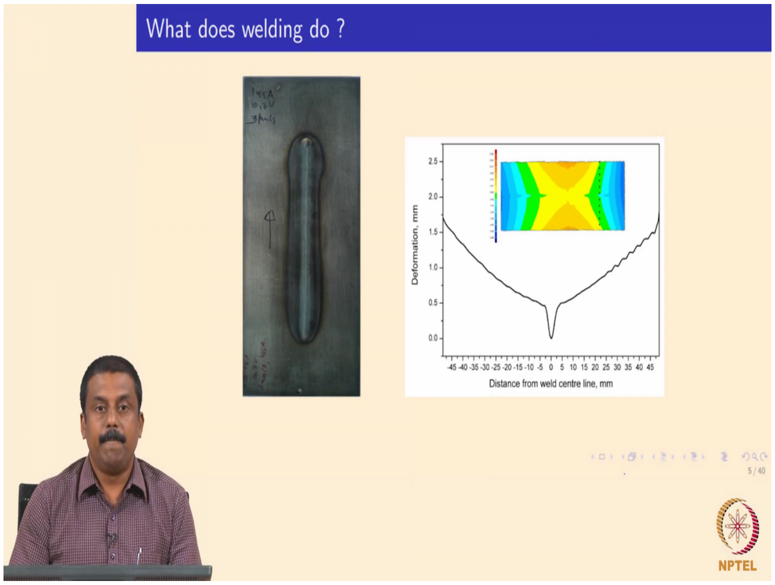

So, what does welding do to iron and steel for that matter is any material? So, they if you look at a microscopic affect the weld if you look at it and then so you would see two distinctive effects: So, one is so when you do weld and you also have an anisotropic thermal expansion because you have a varying amount of phases. In this case we have and trip steel for example your three phases ferrite, carbon bainite and retained austenite.

The thermal expansion of these three phases can be different entirely. And when you have a base microstructure when you are heating up to a temperature each phase can expand and contract. I mean you are doing heating and cooling entirely different. So you may have an unimaginable strain development when you apply a weld thermal cycle. And apart from that we also have and these strains that are evolving due to phase transformations.

So, these are all added together and then can lead to yes the severe and residual stress development in and around the world. So, the first effect you see in the macroscopically is the evolution of regional stress and this stress can lead to a distortion of the plates. So, we are not going to in detail into the residual stress evolution and the distortion.

So, we can assume that you know when you are welding and because of innovating a strain development in various levels mainly in three levels yeah I mean in macroscopic level, in a phase level, in a grain level as well as in the crystal level, so, you may expect a strain development and this strain can lead to distortion. And apart from the macroscopic strain effect of course you also have a temperature effect.

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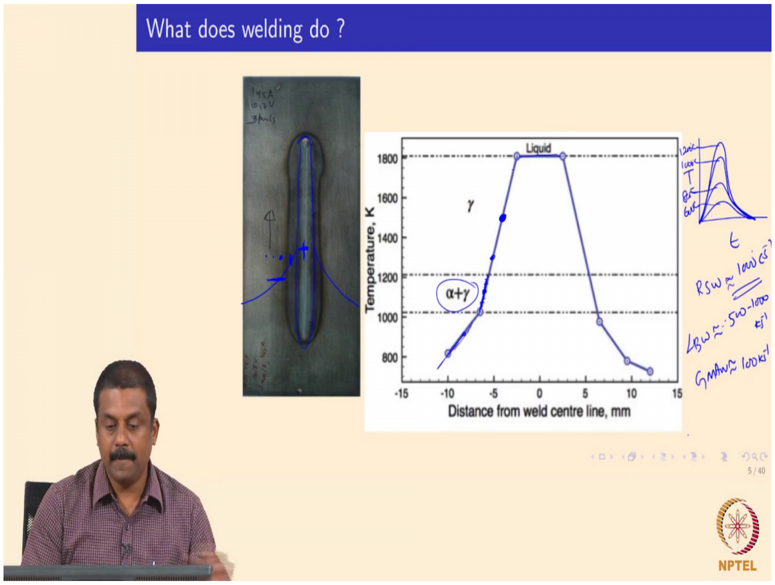

So, when you play in a weld thermal cycle and in and around the weld regions, regions also heated up to various peak temperatures and they are heated up to melting point. For example if you have a plate, welded plate, we are the weld at the middle. So, bead on plate made with the GMAW in this case and so you have weld center line. So, weld centerline over here so the welded regions and so the temperature reached is much higher than the melting point.

So, here you form a molten pool and if you move away from the weld center line your peak temperature decreases as a function of distance from the weld centre line. So the peak temperature reached around the fusion boundary will be close the melting point will be less than the melting point on the fusion boundary and when you move away from the fusion boundary the temperature decreases significantly.

So, if you look at the peak temperature you know based on and from the phase diagram you can look at it, so when the temperature reached above the a three line we call the lectures my lectures on the phase diagram. So, when the temperature reaches above the three temperatures, so you have a complete oxidization. And then the heating and cooling rate would dictate the amount of austenite formed.

Suppose if you have a temperature reached is much higher even if the very fast heating rate. So you may have a fully austenite microstructure and subsequently you can cool it back to fully martensitic microstructure. So, if you move away obviously the temperature, a peak temperature reached, it is also, can also fall in between the intercritical annealing regions, so where you have a region heat affected zone.

Say for example somewhere over here and you may also have a temperature reached to inter critical temperatures and you may also have a in inter critical annealing treatment. For example and when you have a temperature reached below A1 temperature where you know you may not see any phase transformations but there could be some other effects. For example if you have martensitic microstructure say in dual phase steel we may also temper at the martensite.

The region when the temperature reached, when the temperature is below the A1 temperature the trip steel and you may also have some effect in retained austenite because retained austenite is not stable when you heat it up to higher temperatures okay. So, we will see in the effect, so based on the welding process the heating and cooling rate can also change. So, typically if you look at the various regions, so now if you look at time temperature graph, say for example, region somewhere over here, where the peak temperature reached say about 1500 Kelvin.

Somewhere around say 200 degree centigrade so the peak temperature if it reaches 1200 degree centigrade at this point so you will have a heating total energy centigrade and subsequently cool to room temperature. So, say for example about 1200 degree centigrade if you move away from the weld centre line this is somewhere over here, so if the peak temperature may be reached to say 1000 degree centigrade. So, then you will have curves something like that at that point.

And similarly if you move away elsewhere, so you may also go to the inter critical region where the temperature can go up to say 800 degree centigrade once we are at a peak temperature reached say this will be 1000 if you say 600 degree centigrade where you have an inter critical regions and if you move further away so far away the temperature may reach say 600 centigrade and you have a thermal cycle developed at this point in this manner.

So, the heating and cooling rate is determined by your and the material thickness and the heat transfer of your material, your local conditions as far as the heat source characteristics. So generally if you have the material thickness for a given material thickness, the resistance spot-welding gives the maximum by heating and cooling rates where the heating and cooling rates can go in RSW in the order of a 1000 centigrade per second;

Whereas in a laser beam welding so we can go up to a few 100 of; somewhere between say 500 to 1000; so whereas, in a GTAW or a GMAW the cooling rates can be controlled in the order of say100 Kelvin per second. And the heating and cooling rate can be controlled in the order of 100

Kelvin second. So, if you look at it in a RSW the distance spot-welding gives the maximum heating and cooling rate as well as the temperature gradients very steep in RSW and then subsequently in GMAW welding.

So, imagine now we know if you are heating up in a 1000 centigrade per second rapidly to an oxidation temperature and cooling back and you can expect an severe heterogenic in terms of micro structural development at various regions and the cooling rates will dictate that you know when you are fully austenite microstructure you will end up getting martensitic microstructure.

And similarly know, when the temperature reached to inter critical region and you will not form a fully austenite microstructure, you will have the two phase microstructure, wherein your austenite can also be enriched in carbon similar to what we looked at when we looked at the integrating annealing treatment. And the based on the temperatures reached you may also have a gradient in the enrichment of austenite.

For example regions reached, where the temperature reached to just below an AC, at A3 then you may have the maximum amount of austenite so you may not enrich the austenite significantly whereas the regions just above the AC3, AC1 and you may have a highly enriched austenite and again so there will be an interplay between the temperature as well as the partitioning and the amount of austenite you form can lead to an increased amount of retained austenite civilization when the peak temperature reached to an integral annealing temperature during welding.

Of course, when there when the temperature reached fully austenite region and you have fully austenite microstructure where so you will not have an benefit of carbon partitioning when the temperature needs to inter critical annealing temperature. So, from this the complex thermal cycle you expect during welding and you may also expect in a very complex microstructure that are generated after welding.

So whatever microstructure we have in the base material a beautiful microstructural generated from the complex thermo mechanical treatment as well as adding alloying elements. Now weld it has its own thermal cycle okay. So, when you are applying such a weld thermal cycle, so you may expect and a very heterogeneous microstructure generated after welding. So, now we will have to understand from the metallurgical point of view how these weld thermal cycle is going to influence the microstructure evolution.

And from this understanding and we can also mitigate this weld thermal cycle in loss after we could look at how we can engineer these thermal cycles, so that now we can minimize the damage weld thermal cycle does to the carefully designed microstructure.

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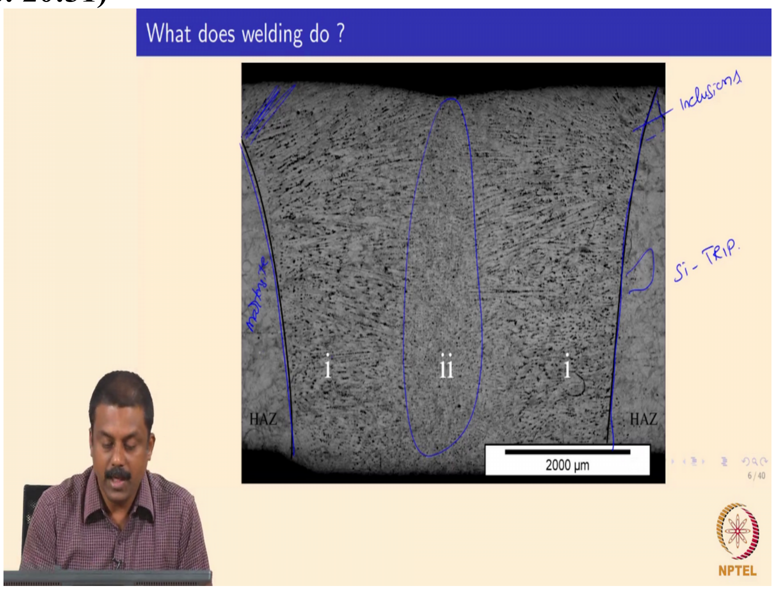

So, this is an overview of weld made using a GTAW, gas tungsten arc welding alarm or variant. So, we just applied in a simple weld thermal cycle. And then, if you look at the weld zone, so, this is the fusion boundary, so what you see over here. And if you look at the microstructure of let us say this is a silicon based trip steel and after GTAW weld that is a simple bead on plate weld you see a columnar solidification.

And you also see in the center line equiv-axis grain, grain mode which is not visible but so the day becomes equiv-axed. And then you also see these black dots that are actually inclusions of a non metallic's, okay. And you also see the heat affected zone. Now you see the coarse grain can see heat effected zone on this is completely martensitic microstructure where the temperature reached here is fully austenitic. And then subsequently when you cool it and then, it becomes fully martensitic.

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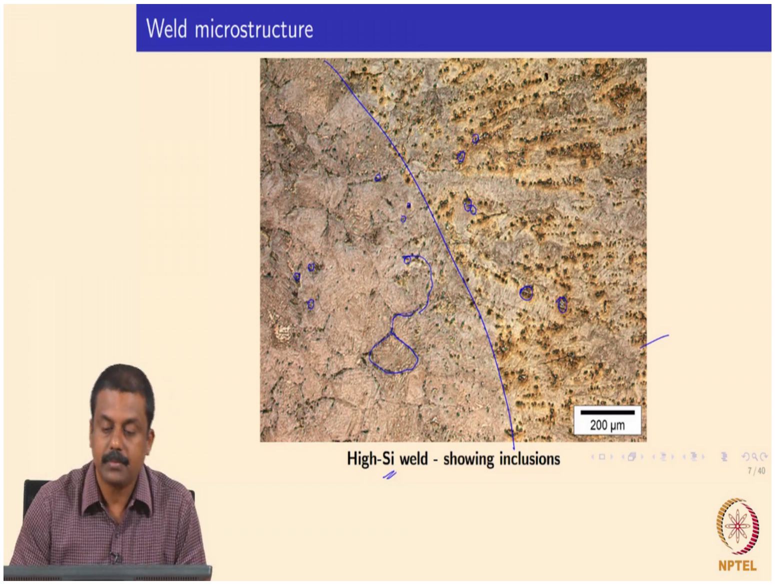

And weld zone is if you look at it in a closely, in a slightly higher magnifications in the same steel in High Silicon weld, you see it; see this is the fusion boundary. The heat affected zone is fully martensitic and with the grain boundaries are decorated again with the nonmetallic inclusions. And so this is again, this is not an ideal weld condition when we made. And this is sure that you know when you use a conventional weld thermal cycle and you have an severe intrusion formation and High silicon steel weld.

And we will see the two major effects of weld thermal cycle here. Now if you make an a simple welding case, so you will have the formation of the inclusions, this. And then a complete martensitic microstructure with a when you have a grain boundary melting and you may also have any inclusions that are formed along the grain boundaries in the coarse grained heat affected zone. And this is in High silicon steel case when you have an;

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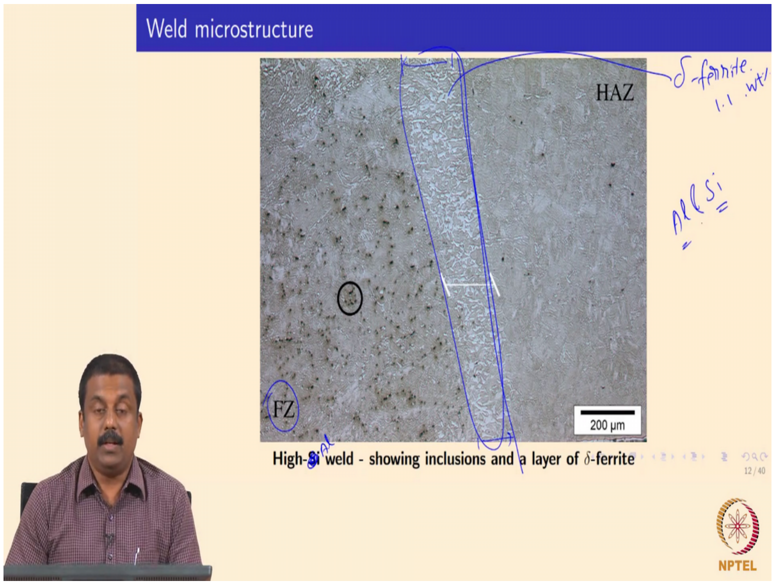

So, when you have a high aluminum case and the weld showing in the microstructure if you look at the high aluminum weld so what you see over here apart from the inclusion formation inclusions of non-metallic inclusions in the diffusion zone. So, this is your fusion boundary and apart from the inclusion, you also see a distinct layer of under fusion boundary a stabilization of a phase. And in this case so this is a delta ferrite.

So, recall the aluminum iron carbon phase diagram with influence of aluminum so when I was showing the phase fields and we showed that by addition of say one point one percent weight percent of aluminium so your delta ferrite is also stabilized to much lower temperature. So, so what we are seeing over here is the effect of aluminium. And aluminium can lead to stabilization of delta ferrite in the fusion boundary because of the partitioning of aluminium during solidification to the prolific delta ferrite.

So, we will see how this happened, the metallurgical reasons behind this stabilization. So you need to see you can understand from this microstructure, the effect of alloying elements very clearly. So when you add a higher amount of silicon aluminum and both aluminium silicon are highly oxidizing. So, the aluminum readily forms oxides and these oxides now it can form at very high temperatures above a melting point.

The moment you have where the oxide formation you may also have an enrichment of all other alloying elements on to its oxide formation and can lead to the formation of nonmetallic inclusions. So, by increasing the aluminum silicon concentration and which we are which are needed to stabilize retained austenite we may also form nonmetallic intrusions invariably in the weld zone.

In aluminum based trip steel apart from the inclusion formation and we may also have a soft zone of delta ferrite that can be stabilized in the fusion boundary okay. So, we will see in detail about the mechanism of impression formation and the aluminum partitioning aluminum behavior of aluminium partitioning in subsequent classes. And then, we will see the effect of the other alloying elements.

For example phosphorus and boron in advanced high strength Steels, how the welding microstructure can influence can be influenced by the partitioning of these alloying elements. So, first we will begin with the addition of Silicon aluminum. So as I already showed in these two microstructures because of the highly oxidizing nature of the aluminum silicon both elements form oxides, oxide inclusions.

And subsequently they may also attract other alloying elements and then leading to the formation of nonmetallic inclusions. And the aluminium because of the affinity to Delta ferrite during solidification and upon reaching critical limit it can also stabilize and the fusion boundaries upon solidification.

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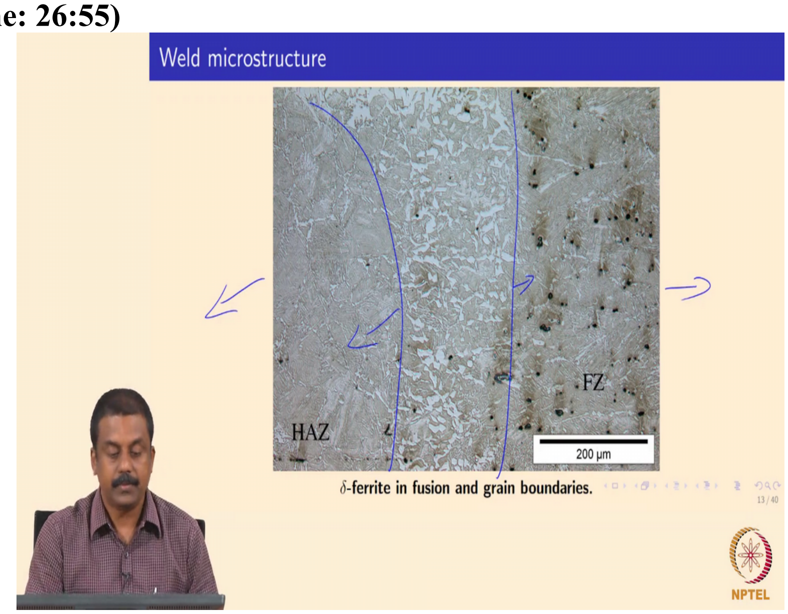

So, the delta ferrite, we can also very clearly see that the assembly system delta ferrite at the fusion boundary. So, they having a delta ferrite at the fusion boundary bit in the sandwiched between the martensitic phase microstructure is extremely vulnerable because the delta ferrite considered to be softer than the adjoining the matrix which is fully martensitic, in this case and if you have a soft delta ferrite region between a martensitic microstructure.

So, obviously when you are loading this structure and then intense of shear load, your load will be strain will be partitioning to the fusion boundary and expect failure of the fusion boundary when you are loading.

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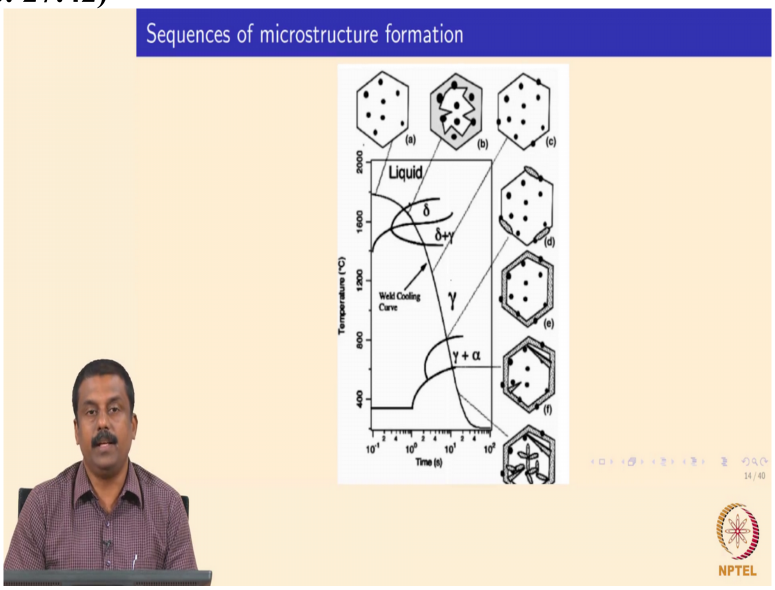

So, far what we have seen here in these classes, so we looked at the welding metallurgy, the very basics of welding metallurgy in advanced high strength steels, so how typical weld thermal cycle evolved during welding. And so we also looked at the chemistries of trip steel and with the addition of silicon aluminum is very much needed to stabilize austenite. But when you have an silicon and aluminium present in the weld pool because of the highly oxidizing nature of these elements and they may form an inclusion, nonmetallic inclusions.

And the partitioning behavior of aluminum to the solidifying phase can stabilize the unwarranted phases in the diffusion boundaries. So, we looked at in detail the role of these alloying elements in the evolution of microstructure and how the weld thermal cycle can influence the microstructure evolution with the presence of these alloying elements in subsequent lectures, thank you.