Welding of Advanced High Strength Steels for Automotive Applications
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Lecture - 05
Introduction to Dual Phase Steel and TRIP Steel Heat Treatments

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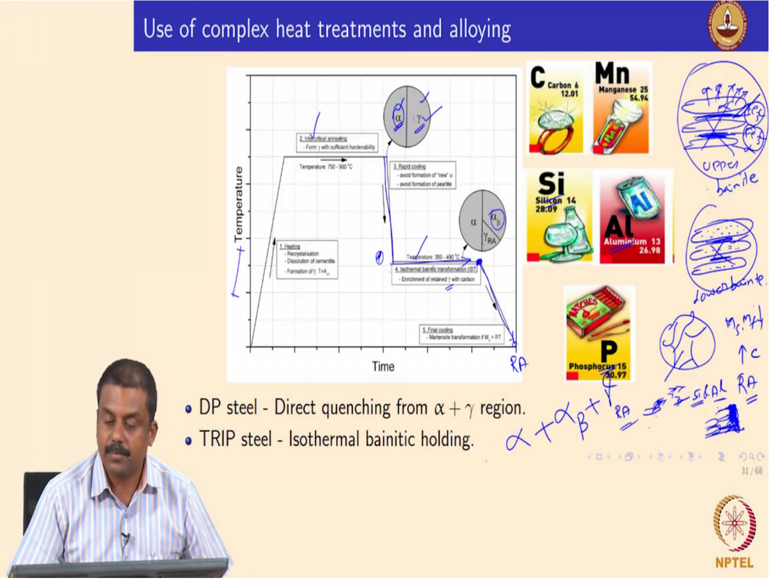

Use of complex heat treatments and alloying

- DP steel - Direct quenching from $\alpha+\gamma$ region.
- TRIP steel - Isothermal bainitic holding.

Quickly recall from this slide we were looking at the microstructure of dual phase steels how we get the two phase microstructure ferrite and martensite microstructures right. So, in this instead of taking it to fully austenitic region we are taking the Steel to a temperature where both ferrite and austenite are coexisting that region we all known as alpha + Gamma region or inter critical region right inter critical region. So, the advantage of doing that inter critical in the heat annealing treatment is as I already explained.

So this is your eutectoid phase diagram suppose if you still as 0.2 weight percent carbon and we are taking to A temperature region where both the ferrite and austenite phases are coexisting. Suppose if I am keeping the temperature somewhere around 800 degree centigrade are so. So what happens here holding it here so you form austenite with enriched amount of carbon? So, the amount of carbon in austenite is always higher than the ferrite and at this temperature even though you have a 0.2% bulk carbon concentration.

Your austenite carbon concentration will be slightly higher than the; your bulk. So, doing so we are also enriching the austenite in carbon and subsequently if we have a microstructure containing both ferrite and austenite, the austenite with enriched carbon if you cool down to room temperature and because of increased hardenability this austenite; so we may even form martensite at much lower cooling rate then you generally need for steels containing 0.2% carbon. It means that so by enriching the austenite by carbon, so we are also reducing the critical cooling rate required to form martensite.

Subsequently if you are cool down to this microstructure so you have ferrite and then austenite which for example and this austenite when you cool down to room temperature will transform into martensitic microstructure. So, during this process as I already explained so you are not only to have martensitic ferritic mixture of microstructure and the austenite transform to martensite you will have a volume of expansion, so that volume expansion has to be accommodated ok, so, by means of generating mobile dislocation at the interface between ferrite and martensite.

So, these mobile dislocations are very useful to increase the ductility of the material and the presence of martensite in this region increases its strength ok. So that is the actual idea behind generating the two phase microstructure ferrite and martensite, so increases the strength as well as because of the mobile dislocation that are generating, that are generated during the heat treatment to increase to enhance the ductility of the material ok. This again we are to achieve this heat treatment the critical metallurgical parameter needed are carbon concentration of austenite.

So, this is very critical because in the factory the cooling rate conditions so we cannot really achieve real and I cooling rate like in quenched case, quenching heat treatment. So, with increasing carbon content concentration of austenite we may also have reasonably slow cooling rate. Even in the slow cooling rate we get the martensitic microstructure. And because of this two phase mixture so you also have a reasonable ductility and strength which is actually needed for advanced high strength Steels where we have reasonable strength and the ductility.

And apart from carbon effect we also add other alloying elements for example Manganese to increase solid solution strengthening of ferrite as well as the martensite. And sometimes we also add micro alloying elements for example vanadium, niobium and titanium and these alloying elements again they combine with carbon to carbon nitrogen to form the vanadium, niobium, titanium carbon nitrides. And this precipitates are very effective to provide precipitation hardening in dual phase Steels. So the; if the Steels with strength level more than 600 ma Pascal would invariably I have some amount of precipitation hardening in it.

So, the most common alloying elements that are added in this dual phase steels to strengthen to increase strength of course with the compromise to the ductility they are vanadium, niobium and titanium to form vanadium carbon-nitrides of the micro alloying regions. And these three elements are commonly added to form precipitate of carbonitrides, carbon and nitrides in austenite matrix. And the strength increases significantly based on the size and volume of this precipitates. And of course because of this ductility decreases but again I mean because of the presence of large amount of mobile dislocation during subsequent heat treatment.

You will still get the significant ductility in this steels so that what you are seen in the banana diagram which I showed you earlier that ductility is or even DP 1000 can be still amount 15 to 20% ok. So, apart from dual phase microstructure this graph can also be used to explain the microstructure formation of the trip Steel. The difference between the dual phase heat treatment and trip steel heat treatment yes we have one extra step you see over here around temperature of say 350 to 500 degree centigrade.

So, in this case we have additional holding at this temperature range. So, we take it too to fetch region from the room temperature we go up to intercritical cooling region where we form the mixture of ferrite and austenite ok that is same as dual phase heat treatment. But in real face treatment you directly cool to room temperature right. So, that austenite whatever it is formed during intercritical holding, inter critical holding means holding in two phase regions alpha + Gamma region and in this region again we do the n treatment of austenite in carbon as I have explained.

Given by this phase diagram and instead of cooling it directly to the room temperature as in dual phase Steel and we will be holding at intermediate cooling temperature. Generally the typical temperature between 350 to 500 degree centigrade and what we do in this temperature recall my CCT diagrams. When you are holding at this temperature isothermally so the austenite is most probably will be transforming to bainite because of the following element what we have right. So, we would transform whatever the austenite actually forming during this intercritical treatment to bainite ok.

And we do one trick so we do not form bainite here classical bainite I explained in the earlier classes. So, what is bainite again it is a mixture of ferrite and cementite and the different morphology is pearlite. So we can have upper bainite or lower bainite. So, the upper bainite the microstructure so we have a ferrite platform and the carbon subsequently migrate to on the adjoining regions of in the ferrite lath and you end up cementite at the inter-lath between for example differate lath. You have ferrite and this cementite. So the upper end bainite microstructure typically is like this.

So now we do a small trick by adding some alloying elements in order to suppress this cementite formation. This inter-lath cementite formation so this can be inter-lath cementite formation in case of upper bainite right or it can also be interlath cementite nucleation as in the case of lower bainite formation. So, this is for example lower bainite. So, now if you look at these diagrams I have two special alloying elements in fact we can also include another one, mainly the silicon and aluminum some extent Phosphorus as well.

So, this Silicon Aluminium is added in trip Steel for very specific reason to suppress the formation of cementite ok. So if the cementite is suppressed during the formation of bainite when austenite is transforming to bainite first is ferrite nucleating, so where it forms. And then these carbon atoms try to go out of the ferrite but because of extremely low solubility of silicon and Aluminium and cementite. So what do you mean by solubility the cement tight lattice cannot hold cannot keep the aluminium atoms.

Suppose imagine you have the austenitic micros structure yeah two phase microstructure from the inter critical region for example this is austenite grain so, if you make it bigger this is your austenite grain and this austenite grain is hold now the temperature regions where are you form bainite ok. Now at this temperature what you are happen obviously you tend to form bainite microstructure the austenite will transform to bainite during this holding.

So first you nucleate the ferrite lath but this ferrite lath cannot have a carbon right the carbon has to be pushed out off the ferrite to the adjoining austenite region in the conventional bainite what will happen the moment the carbon atom go then this segregate and then format cementite lath in between two ferrite laths. So this austenite is containing more amount of silicon and Aluminium or silicon and or aluminium ok. The moment you have Silicon aluminium in solid solution of austenite the nucleation of cementite is extremely suppressed.

That means that the carbon is used going out ok but cementite cannot nucleate why because this cementite lath cannot have a silicon and Aluminium in its presence. So, if cementite has two nucleate apart from silicon and Aluminium this atom should be pushed away. But the diffusion of silicon and Aluminium is extremely slow and the end of delaying the formation of cementite at the inter-lath locations. So what will happen because of that your austenite is actually getting enriched in carbon.

It keeps on enriching because of the formation of ferrite and during bainite formation and this carbon atom is try to go ferrite even if it is goes it will try to enrich the austenite because we are suppressing cementite formation. So at the end of the; towards the end of the transformation the bainite bainitic ferrite ferrite laths in the bainite would grow with an extreme enrichment of austenite carbon untransferred austenite ok. So, the carbon atoms are all the moving away from the bainitic ferrite, the ferrite lath in the bainite and they are enriching the untransferred austenite considerably.

And we do not nucleate cementite because nucleus of cementite is retarded by the presence of silicon and Aluminium atoms in the austenite matrix. So, what will happen then now so you are enriching the austenite in carbon so much you significantly reduced the MS and the MF temperatures ok? So, the MS temperature and MF temperature ok decreases by increasing in carbon concentration right ok. So, what will happen now so your; forming the bainite without cementite. In principle you are forming only bainitic ferrite.

Only the ferrite laths during the bainite formation only the ferrite laths during bainite formation. And you are suppressing the cementite nucleation when during this bainite transformation. By suppressing the cementite transformation what are you doing you are enriching the austenite which is untransformed during the transformation significantly in carbon right. Because if cementite is not nucleated you are untransformed austenite is enriched in carbon significantly is it not. So, now this upon sufficient enrichment so there is also incomplete bainite transformation because the austenite now stabilized.

Because of the partitioning of carbon bainitic ferrite and upon sufficient enrichment bainite transformation would not progress. And I will explain some thermodynamics in next slide. And you can assume that upon sufficient enrichment in carbon the austenite which is untransformed would remain as austenite upon subsequent cooling. Because next transformation when you may cool here obviously martensitic transformation. But if you are enriching austenite significantly in carbon you are MS and MF temperature would decrease much further.

MF temperature would go below room temperature and MS will significantly reduced there about 200 to 250 degrees are so. So, the amount of retained austenite which is untransformed during this transformation would be retained as a retained austenite. Yes it is clear I will explain again so we start with two phase intercritical microstructure which is ferrite and austenite. So, austenite is already enriched in carbon this line you imagine austenite is already enriched, and this austenite is cool to temperature regions where you would have isothermal holding to form bainite.

But this bainite formation is happening without the formation of cementite ok. How do you suppressing this cementite by adding silicon or Aluminium ok. If you have silicon aluminium what happens you suppress this nucleation of cementite during bainite formation. How you suppress the cementite formation because cementite lattice solubility of silicon aluminium and silicon cementite lattice extremely low. If you want to nucleate cementite silicon aluminium atom it is pushed away from the nucleation site of cementite right.

But that is not possible by in Kinetic terms so you suppressing cementite nucleation bainite and bainitic ferrite laths would start growing by pressing the carbon to untransformed austenite. Upon sufficient enrichment of carbon in austenite ok. You all know that MS temperature and MF temperature would decrease significantly. Then what you will happen then if you further cool isothermal holding to room temperature you would end of stabilizing significant amount of retained austenite at room temperature ok.

And is retained austenite critical right for mechanical properties that is what we saw in previous slide. And this retained austenite transforms transforming to martensite upon loading to causing by causing stress dual transformation and that leads to increasing in plasticity ok. And that is why these steels are known as trip steels why what do you mean by trip Steel is transformation induced plasticity.

So the enhanced plasticity induced by the transmission of austenite to martensite upon loading and how do you stabilize the austenite as I already explained by surprising the cementite formation during bainite transformation ok. How do you suppress cementite by adding Silicon or aluminium? How does how do these elements suppressed cementite transformation because Silicon solubility of silicon and Aluminium cementite is very low ok. So if cementite austenite create Silicon atom and Aluminium atom will pushed out but the diffusion rate of silicon and Aluminium at this temperature was very low ok.

So, barely more aluminium atom to create cementite, so therefore when the bainite forms it is just forming a single phase as bainitic ferrite without the nucleation of the cementite and during this process we all know that ferrite soluble carbon is much low so the carbon has to go out to untransformed austenite is it not. And sometimes the austenite enriched in carbon and upon sufficient enrichment you MF temperature will go to below room temperature. Subsequently when we cool down from the temperature to room temperature right your austenite would be stabilized yes it is clear.

So, this is how we get 3 phase microstructure. So what are three phases in trip steel ferrite which is actually formed during critical annealing and then we have bainite which is actually formed from the austenite that is formed during the intercritical annealing ok. But this bainite is not a conventional classical bainite ok. So, this is not a conventional classical bainite you will have only bainitic ferrite right we will have only binetic ferrite and then some untransformed austenite though this treatment up to this point.

For example in this graph and then subsequently when you cool back this austenite, some austenite maybe transform into martensite that is very insignificant. But majority of the retained austenite established here would be stabilized to room temperature right. So we will end up getting three-phase microstructure in trip steel ferrite bainite ok bainitic ferrite this not a conventional bainitic it is bainitic ferrite plus you have a retained austenite right. So, this is the three phase microstructure which is typically seen in the trip Steel microstructure.

So the critical path to generate these three phase microstructure is this isothermal bainitic holding we are doing the isothermal holding at this temperature ranges between 350 to 500 degree centigrade to enrich the carbon enrich austenite carbon during this treatment ok. So, that the austenite can be retained at room temperature is clear good. So, we will look at in further detail microstructure of trip Steel.

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Use of complex heat treatments and alloying

Steels invariably contain complex microstructures to generate demanding mechanical properties.

As I explained typical trip steel microstructure is shown in this figure we have ferrite which is actually stabilized during the intercritical annealing and then you also I have austenite that is formed during this intercritical annealing treatment. But this austenite is subsequently transformed to isothermal bainitic microstructure during IBT the isothermal bainitic holding and that holding during that isothermal bainitic holding between 350 to 500 degree centigrade and they are transforming the austenite from the inter critical annealing to bainitic ferrite right.

Say for example this is the prior austenite boundary so it will be transforming some of this austenite into bainitic ferrite during this process we will push the carbon atom to untransformed austenite and upon sufficient enrichment of carbon the bainitic transformation ceases. And then the carbon concentration for example this last night is so high and subsequent upon subsequent cooling to room temperature this austenite cannot transform to martensite because MF temperature is lower than room temperature and then this austenite is retained as a retained austenite.

Now this microstructure contains three faces right ferrite brown here it is bainitic ferrite which is for example which is bainitic ferrite and then the white bluish high lines over here and here these are all retained austenite. You see for example in this grain this is our prior austenite line boundary during intercritical annealing now you see that we have the formation of bainite for example happening here and then carbon is also getting push to untransformed austenite is it not.

And then a point sufficient enrichment you see this stabilizes of retained austenite on this regions ok. So now we have a three phase microstructure; microstructure containing ferrite, bainitic ferrite and retained austenite right. So we have ferrite, bainitic ferrite and retained austenite. Again the trick race addition of silicon or Aluminium ok these two guys help us ok stabilising the retained austenite buy suppressing the cementite because that is very critical right. So cementite separations lead to the enrichment of austenite in carbon.

Upon enrichment we reduce the MF temperature so that these austenite can be stabilized upon subsequent cooling after the bainitic treatment to room temperature ok. And the presence of retained austenite this also critical in this microstructure generally we have about 10 to 15% of retained austenite in trip steel. And this austenite in the microstructure transforms to martensite upon loading during this transformation we enhance plasticity as well as these austenite transformation to martensite during loading.

We also regain gain some strengthened toughness advantage in this treatment. So I like to say as well from silicon and Aluminium the modern trip Steels and modern Automotive Steel they also have some amount of phosphorus ok. There are you not problem with addition of silicon and Aluminium in large amount. Generally in trip Steel in the conventional trip Steel we can classify into two ways Silicon based or aluminium based in trip steels. Roughly if you know in the silicon based trip Steels the Silicon concentration go up to 1.5 weight %.

In aluminum based trip steels concentration go up not more than 1% maximum of 1.1 there about it is not more than that is the reason the metallurgical reason for not adding more than 1.1 weight percent aluminium that I will discuss in subsequent classes. You can assume that there are two classification of trip Steels one is Silicon based and the other is aluminium based. The Silicon based trip Steel is Silicon concentration is about 1.5 apart from we have manganese which can go up to say 1.5% and carbon typically around say1.2%. And there are I already explained there are some inner ring problems with the both silicon and Aluminium based trip Steel.

Because when you have Silicon high amount of silicon in steel galvanizability is severely affected because of the oxide formation that significantly affect the occurrence of the zinc give during the ionizing. So there are lot of development that were done to replace Silicon so one of that development is to replace silicon with aluminium. Aluminium is also very effective cementite suppression. So it suppresses the cementite as silicon does. Aluminium is very poor solid solution strengtheners unlike silicon. Silicon is very effective ferrite solid solution strengtheners aluminium solid solution strengthening is not as effective as silicon or manganese.

So, the strength gain in terms of solid solution strengthening by adding Aluminium is not that significant. So, we need to add other alloying elements which would increase the solid solution strengthening as well as it also I have cementite suppression capability. So, for example one such elements is phosphorus one such solid solution strengtheners ok. And phosphorus is also known to suppress cementite formation we can attain that advantage and also it is not known to cross oxide formation in steels.

But phosphorus very effective solid solution strengtheners and also it is known to suppress cementite formation. So there are some developments by adding somewhat increase amount of phosphorus in steels so that we can increase our strength when you have aluminium based trip stills. But Phosphorus is extremely notorious element during welding ok yeah in terms of hot cracking susceptibility to the phosphorus extent notorious. So yeah in steel makers they generally do not generally worry about welding but as a welding engineer we have to worry about weldability as well.

So you can add first Phosphorus to some slightly higher amount then the conventionally used. Because of this addition of Phosphorus the weldability of this material is affected extremely high. But yeah so in; to generator microstructure in a steel mill we can increase the phosphorus to 0.001, 005 to 0.01 that is a phosphorus range. But in trip Steel in order to make use of effective of Phosphorus in suppressing cementite and causing solid solution strengthening the Phosphorus concentration can go; yeah can be increased to for example 15 to 0.02 extremely high phosphorus. But there are some steel makers who explored use of phosphorus to stabilize retained austenite.

But then with d compromising with the compromise to weldability ok, so these are the common alloying elements in trip Steel we have carbon Manganese, Silicon and or aluminium and some amount of phosphorus ok. So these alloying elements are extremely important to get these three phase microstructure. As I explained with this align elements and the heat treatment we cannot get the multiphase microstructure ok. You need to understand that so we need thermal cycle which I have already explained two stage processes we need intercritical annealing temperatures.

And then subsequently cold to immediate temperatures where we keep the Steel isothermally to form bainitic ferrite formation during this process we suppress cementite by this we enriched the untransformed loss in carbon. Upon sufficient enrichment the austenite cease to transform to bainite subsequently to cool back to room temperature and to cool room temperature and because of the enrichment and in carbon numbers MS temperature and MF temperature decreases significantly MS temperature goes down below room temperature.

And whatever austenite is actually untransformed during isothermal holding is stabilized into austenite ok typical mixture we have 10 to 15% between austenite. So it is about 30% bainite ok remaining 6o to yeah around 60? Around 50 to 60% of ferrite you may have in the microstructure ok and again so imagine such a complex heat treatment and the alloying elements needed to generate such a beautiful microstructure what we seeing in this slide. And with this microstructure we achieve the demanding mechanical property that I have explained with high strength and ductility to make automotive components.

So, now question arises now so we have very I amount of alloying element amount of phosphorus, aluminium, silicon all of them are added to get the beautiful microstructure and when you do welding we cannot control the heat treatment thermal cycle as you do it here. Welding as its own thermal cycle ok so we cannot isothermal hold it in a production process for a long time in automotive especially in automotive industries because time is money.

So, we need understand how the alloying elements behave how they segregate and how they partition how they actually migrate during solidification and subsequent transformations while applying isothermal cycle. From that understanding and we can develop thermal cycles that are suitable welding the Steel and trip Steel and dual phase Steels. To summarise we look that 2 heat treatments that are used for developing dual phase microstructure ferritic and matensitic microstructure. And thermal cycle heat treatment used to generate trips steel microstructure containing ferrite carbide free bainite and retained austenite.

And the role of alloying elements in the trip Steel for example silicon, aluminium and phosphorus and how they suppress cementite formation and because of suppression of cementite formation and how we enrich the austenite in carbon and to retain some amount of retained austenite at room temperature.