Welding of Advanced High Strength Steels for Automotive Apllications
Prof. Murugaiyan Amirthalingam
Materials Joining Laboratory
Department of Metallurgical and Materials Engineering
Indian Institute of Technology-Madras

Lecture - 06
Thermal and Mechanical Processing of TRIP and Hot Forming Steels

So, while explaining the stabilisation of austenite during bainite transmission. I used and one sentence known as incomplete reaction phenomena okay.

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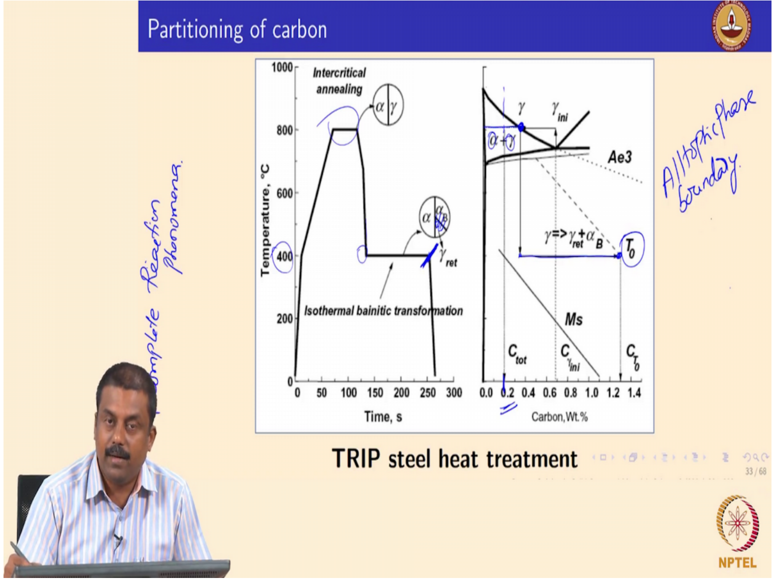

Partitioning of carbon

TRIP steel heat treatment

That means that the bainite when you are; when it is transforming from the austenite it ceases to transform upon the sufficient enrichment of carbon in austenite right. So, incomplete bainite reaction or incomplete reaction phenomena so that is actually a governed thermodynamically which is actually shown in this file I will explain as well. So, suppose if you are cooling the two phase microstructure ferrite and the austenite to a temperature say are about in this case 400 degree centigrade.

And you form bainite without the formation of cementite right. So, it will be only bainitic ferrite and when during this formation the austenite is getting enriched in carbon. But upon say some moment up upon and a critical enrichment level the reaction stops the bainite reaction bainite transmission bainite formation from austenite does not continue till at the end okay. So, when the austenite is enriched to a critical limit the bainite reaction stops okay.

So, so that is why the bainite transformation is known as incomplete reaction phenomena and this is actually the critical carbon concentration upon which at this critical carbon concentration the reaction ceases to exist that critical carbon concentration is defined by here is a t0 which is thermo dynamically known as allotropic phase boundary. So, what happens here again so this is a phase diagram I superimposed to a heat treatment thermal cycle.

So, what we doing it we are taking into integral temperature right so this is a temperature for example here say this is your a total carbon concentration I already explained say 0.2 and we are taking in two phase regions where both ferrite and austenite is coexisting and we form microstructure say for example 60% ferrite and 40% austenite and your 40% austenite carbon concentration is given by this point right that will be higher than your bulk carbon concentration right 0.2.

Now we are cooling the microstructure of 60-40 for example or even say 50-50 no problem and you are cooling this austenite to temperature regions of the isothermal bainitic holding and not this holding and we are forming bainite without cementite formation and during this process the carbon is pushed towards the untransformed austenite right until what point so until the point is known as a t0 or the allotropic phase boundary okay.

So, allotropic phase boundary is defined by the definition is the free energy of ferrite and austenite is same and for a given company concentration okay.

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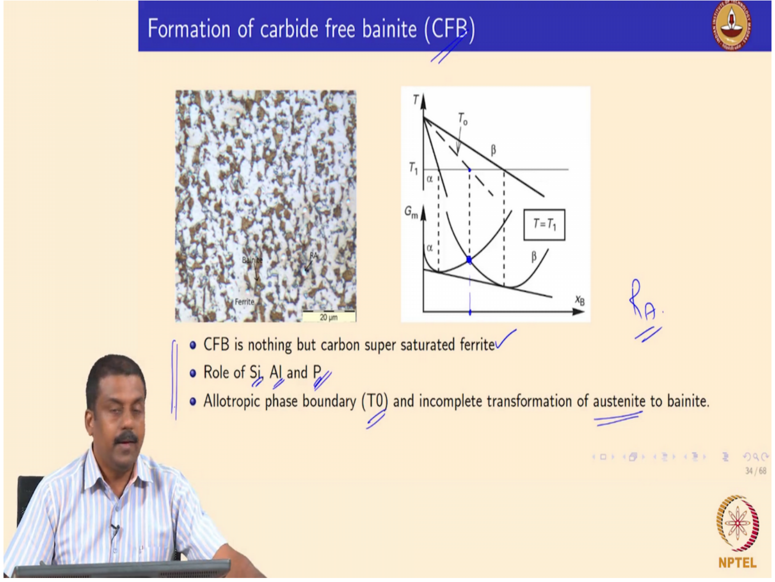

Formation of carbide free bainite (CFB)

- CFB is nothing but carbon super saturated ferrite
- Role of Si, Al and P
- Allotropic phase boundary (T0) and incomplete transformation of austenite to bainite.

So, we will explain in previous slides for example the point at which the free energy is the Gibbs energies of ferrite and austenite it becomes equal at a given carbon concentration okay. So, that carbon concentration is known as T0 or allotropic phase boundary ok. Say for example at a temperature T = T1 at this temperature the point at which the both ferrite and austenite would have same carbon concentration that point is known as a T0 allotropic phase boundary.

So, until the carbon concentration reaches that point okay you would have a binary transmission so once they were austenite carbon constellation reaches the T0 carbon the carbon concentration at which both the right and austenite will have a same Gibbs energy okay and your transmission ceases that means that no more transformation of austenite to bainite, a bainitic ferrite okay.

So, that is the reason we stabilizers we stabilize austenite during this many transmission and the critical point is here is we need to enrich okay. So, if we enrich the remaining austenite with carbon you reach T0 much earlier than if you form cementite. So, you would significantly if we retain the austenite because of this incomplete reacting phenomena driven by the enrichment of carbon in austenite by the suppression of cementite.

And this austenite subsequently when you cool to room temperature right and yeah you cannot transform to martensite fully because of decreasing in the MS temperatures below say MF temperatures below room temperature okay. And so this is thermodynamics of this tribulation in retained austenite. So, it is driven by the incomplete reaction phenomena of bainite and austenite ceases to transform to bainite upon enrichment to T0 carbon concentration okay.

To summarize okay so the formation of carbide free bainite is very critical for trips steel micro structure. So, carbide free bainite is nothing but supersaturated ferrite okay so there is no cementite. So, you found ferrite with slightly higher carbon concentration you suppress the cementite so role of silicon Aluminum phosphorus is very critical okay, so, because silicon aluminum suppress the cementite formation and also as well as phosphorus if you add.

And because of the suppression of cementite you can enrich the austenite the one the carbon concentration austenite reaches to say T0 carbon concentration and the austenite cannot transform to bainite or any diffusional transformation. So, only diffusion less transformation is possible. But yeah because of MF temperature decrease you would stabilize retained austenite at room temperature okay. So, the all these three is important you have bainite it is nothing but a super saturated bainitic ferrite okay.

In trip steel and silicon, aluminum and the phosphorus additions are extremely important to suppress cementite formation. And the concept of T0 the allotropic phase boundary which is actually determines your the dissipation of the bainitic formation from the austenite lead to stabilize the retained austenite in trip steel microstructure okay. I hope it is clear for you how we stabilized this beautiful 3 phase microstructure in trip steels. These three or the critical points you need to remember.

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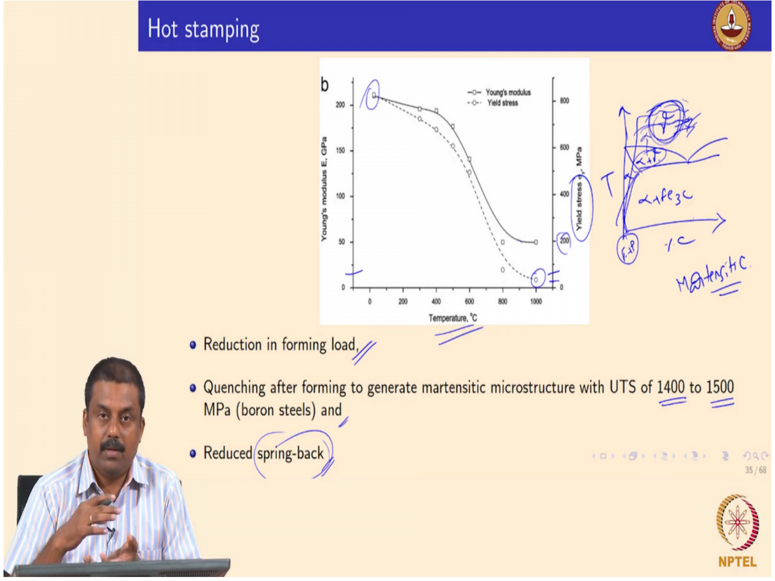

Hot stamping

- Reduction in forming load,
- Quenching after forming to generate martensitic microstructure with UTS of 1400 to 1500 MPa (boron steels) and
- Reduced spring-back

So, we will move on to the next generation next microstructure of advanced high strength steel so we looked at DP and trip and the third advanced high strength steel's is hot stamping Steel's okay. So, before going to the microstructure of hot stamping, hot stamping of micro structure is very simple it is martensitic after hot forming hot stamping okay. So, if you take a martensitic microstructure and if you want to deform at room temperature it is extremely hot okay.

So, you need to have enamors amount of mean load to deform the martensitic microstructure okay and but somehow we can overcome the problem of ductility by starting a simple pearlitic ferritic microstructure okay. So, pearlitic ferritic microstructure are easy to deform compared to martensitic microstructure but yeah if use a conventional pearlitic ferritic microstructure yes I showed you in a banana diagram strength cannot be increased to beyond a certain ma Pascal.

So, for example mild steel and HSLA if you look at it your UTS would be around say 400-350 to 400 ma Pascal in conventional HSLA or mild steel even less than that. So, we take the pearlitic ferritic microstructure and we heat it up to temperatures where you have fully austenitic micro structures okay. In hot stamping case we do not deform at room temperature but we will deform in the austenitic condition okay.

So, we will take it if we heat up the sheets to high temperatures and we transform the microstructure into fully austenitic regions. So, what do you do in again the eutectoid phase diagram eutectic regions of the iron carbon phase diagram? So, we have austenite and the see inter critical region we saw in the previous slides okay. This temperature and carbon so we heat it up heat up microstructure containing ferritic pearlitic to a single phase austenitic region and then we do a deformation okay.

So, why do what advantage you would gain by doing it by carrying out deformation austenite region because material softened significantly when a temperature increases say this slide I showed you a graph here one of our work which shows Young's modulus and the yield strength it is raised as function of temperature. So, what is yield stress here and it is the onset of plasticity deformation right these yield stress top of each the plastic deformation triggers or plastic deformation initiates.

If you look at this graph okay so by increasing temperature the yield stress decreases significantly. So, you have a significant high yield stress if you have a piss placed hardened material okay and if you are increasing temperature say at around 1000 degree centigrade where you have a fully austenitic microstructure as where the yield stress is not even about 50 ma Pascal okay. So, similarly the Young’s modulus will also it decreases significantly as a function of temperature okay.

So, we can take an advantage of softening of material at a later temperature and by combining the phase transformation upon deformation and we can significantly increase the strength after deformation. So, what we do in this structure so you can start with a very simple ferritic pearlitic microstructure okay you take it to austenitic region and you deform it to whatever shape you want okay and then you cool it to room temperature and during this cooling you convert the entire austenitic microstructure into a martensitic microstructure okay.

So, you form it at then a very soft stage you see that no yield stress is not even 50, 100 ma Pascal okay so you can deform it very easily at austenitic regions okay. And then subsequently quench to room temperature so their component microstructure after deforming could entirely become martensitic then the strength of the component would increased significantly because of the formation of martensite after quenching okay.

So, the advantage of this hot forming is you reduction forming load because the material ductility increases significantly it softened significantly at high temperatures and then you transform the austenitic microstructure upon forming two martensitic and during this process the material gains strength significantly you can reach the strength of 1400-1500 ma Pascal okay. And the other added advantage is there because of the placid deformation of the phase transformation and the deformation high-temperature and both combined would also lead to decreasing in spring back.

What is spring back again through elastic recovery after forming and ok that to also significantly reduce and because of the item by deformation a coupled with the phase transformation of martensite okay? Now the critical here critical metallurgical factor that can influence the hot forming process is your phase transmission temperatures okay generally it is advise to do a hot forming or the forming or stamping in the austenitic region.

Because if you are taking it to inter critical region there are all complexities in terms of microstructure there will be two phases if he is present and there will be stuff partitioning between the ferrite and austenite because they both have different carbon concentration the strength will be different. So, it is generally not advisable to do stamp or format inter critical region. So, you need to take it to a fully austenitic region where your single-phase micro structure you will have uniform carbon concentration or alloying elements concentration.

And then you deform it or whatever rate as well as whatever amount degree of deformation and subsequently you quench it to room temperature generally it is done in press, so you press it up you have to make a component and you hold the component in fresh and cool it to room temperature okay. And during this process the component microstructure and the transforms completed to martensitic microstructure.

And doing this process the strength increase significantly and because of the item by deformation and the phase transformation of martensite formation of martensite you also control this in spring back significantly okay.

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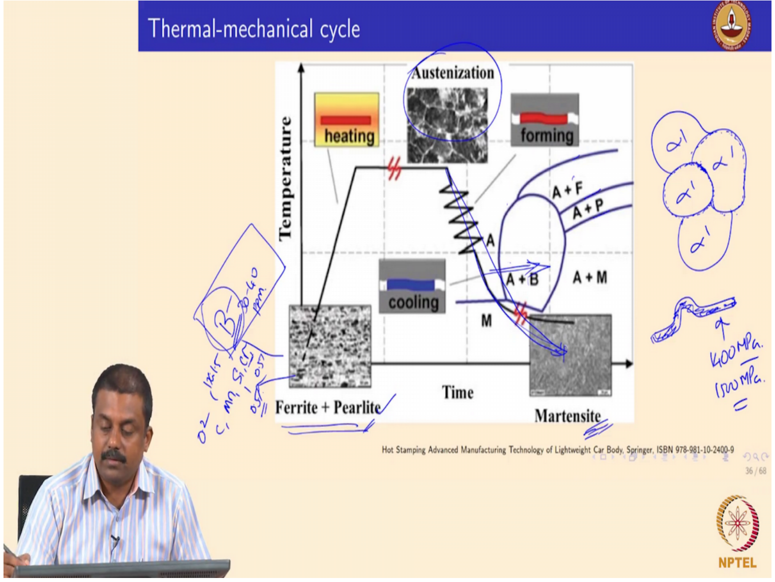

Thermal-mechanical cycle

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And the actual thermal cycle what you use is shown like this so in this graph. The critical factors I will explain in terms of getting the final microstructure so you start with a ferritic pearlitic micro structure okay. So, the common the composition of the hot stamping steel is also similar to what you have in ideal phase steel typical but some special alloying elements that are added in the hot stamping steel.

One such a alloying element is boron the role of boron in handnability I already explained I will also explain again for your convenience during yeah explaining this slide. So, you start with ferritic pearlitic micro structure containing slight somewhat of boron as well it is not more than 30 or 40 ppm okay and the micro structure the other compositions are same as similar to dual phase steel micro structure composition.

So, you will have manganese silicon some amount and chromium okay so you may also have of course carbon say 0.2 it is about 1 to 1.5 also we can say .5 it this steel does not have as much silicon as in trip steel. Only trip steel we have a high amount of silicon in silicon based trip steel or aluminum and chromium is about point 5 and you can also go high and the important alloying element hot stamping steel is boron. Again so boron we have about 30 to 40 ppm okay.

So, now we take the microstructure of simple ferritic pearlitic micro structure and you take it to fully austenitic region so you heat it up you found fully austenitic grains and then you deform it ok. Whatever shape you want to do that and then you; after deformation after forming you cool to room temperature for that what do you need to do the cooling rates would be above the critical cooling rate right. So, you have a CCT diagram that is super imposed and so this is your bainite formation nose so you have a bainitic phase and this is ferrite start and these pearlite starts. They will attend and you will have a martensite sorry the MS line somewhere over here.

And if you are cooling here within slightly slower cooling rate then you would the microstructure would also form to bainite so we should avoid that. So, we need to make sure that the steel is cooled to above the critical cooling rate to needed for a martensite formation. So, the your austenite would completely transform to martensitic microstructure okay. So, I said explained during an in CCT diagram in order to get a complete martensitic microstructure we need to increase the hardnability of this steel significantly.

So, what do you mean by hardnability so we need to push the CCT diagram as much right side as possible okay. Suppose if this line is somewhere over here that is not good right. So, we need to then you may end up transforming austenite into the other high-temperature products say for example pearlite or bainite. So, in order to get complete martensitic microstructure so we will have to have critical cooling rate.

So, yeah for example and decrease to some extent so that even at slow, slower cooling rate or cooling rate generally achievable in a die quenching can give to a fully martensitic microstructure. So, one way of obtaining this is to move these CCT diagrams towards right side, right. And the one alloying element that can do effectively is boron okay. So, boron can increase it can increase the hardnability or decrease the cooling rate needed for martensite formation significantly.

So, how did does the boron? Boron actually you know I mean in austenitic microstructure when you add boron, so boron readily segregates to the grain boundaries of austenite at this temperature range for example the moment boron segregates the grain boundary okay when you are cooling this austenite to room temperature for example here in this case the nucleation of ferrite is retarded okay.

Say even if you form a pearlite bainite you need to nucleate at ferrite lath okay. The solubility of boron in ferrite is also very low okay. And if ferrite has nucleate and boron atom has to be pushed out okay otherwise ferrite cannot nucleate right. So, if the boron atoms segregate the grain boundary it is very difficult for boron atoms to move away from grain boundary because grain boundaries are the most energetically favorable locations for the boron atoms.

The moment where boron atoms comes to grain boundary the nucleation of ferrite becomes sluggish okay because if ferrite has nucleate or it has to push the boron atoms from the grain boundary right which is not possible energetically thermodynamically or even kinetically you can say. So, the nucleation of ferrite is retarded what will happen then if nucleation of ferric retarded this austenite remains as austenite right.

And if austenite remains as austenite and subsequently if you cool back if cool that microstructure there is no partitioning okay. So, it is a simple austenite microstructure if ferrite nucleation is retarded the austenite can fully transform into martensite right. So, because of the retardation the austenite this remains austenite and subsequently when cool to room temperature the austenite may transform to martensite okay.

It is clear so the role of boron is extremely critical to achieve the martensitic microstructure in hot stamping steel because, so because of the addition of boron and we can farm martensite reasonably slow cooling rates and the CCT diagram is moved towards right and thereby decreasing the cooling rate required for a martensite formation always happening because of this segregation of boron to the grain boundaries.

And due to these segregation of boron the ferrite nucleation is retarded and thereby the austenite can be transformed to a fully martensitic microstructure. So, we start with a simple pearlitic ferritic micro structures you conventional micro strucuture say for example in the mild steel and we take it to austenitization and deform it and form whatever way you want and then cool it room temperature okay.

And you get a component for example say deep-drawn cup full of martensitic microstructure a complete martensitic microstructure. So, you start with a very soft reasonably soft material end up fully martensitic microstructure with this strength level of say 400, 1400 ma Pascal okay. So, now again it is boron it is also a; it is not really in a little much element in terms of weldability but roll of diffusion of boron to grain boundaries can significantly change the diffusion of subsequent or other alloying elements.

It may not really determined for the weldability but it can affect a segregation about alloying elements say for example the phosphorus segregation during welding. So, it is really important to look at the role of boron as well during welding which we will see in subsequent classes okay.

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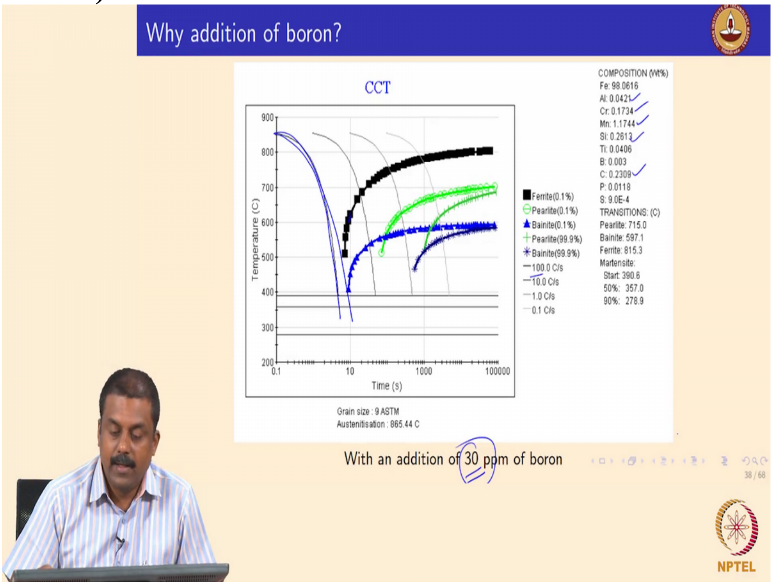

Why addition of boron?

COMPOSITION (Wt%)
Fe: 98.0616
Al: 0.0421
Cr: 0.1734
Mn: 1.1744
Si: 0.2613
Ti: 0.0406
B: 0.003
C: 0.2309
P: 0.0118
S: 9.0E-4
TRANSITIONS: (C)
Pearlite: 715.0
Bainite: 597.1
Ferrite: 815.3
Martensite:
Start: 390.6
50%: 357.0
90%: 278.9

Grain size : 9 ASTM
Austenitisation : 865.44 C

With an addition of 30 ppm of boron

So, this is also the effect I already showed you the how the boron addition effects the CCT diagrams. So, this diagram shows the hot stamping still without any boron we see their critical cooling rates is somewhat it is even more than 100 Kelvin centigrade per second so somewhere over here sorry okay. So, even if you cool it 100 degree centigrade per second you will still form the high temperature products like ferrite and in this case bainite okay.

So, by adding a 30 ppm of boron you already see critical cooling rates needed for a martensite decreases significantly say previous without boron even at 100 centigrade per second you formed a significant amount of ferrite and bainite. Whereas just by adding 30 ppm of boron you see that 100 killing per second you know you have a fully martensitic microstructure okay. So, even if you fully say for example critical cooling rate of 80 killing rate per second you may still get martensitic microstructure. So, you do not change the composition much you have all of them similar like aluminum say chromium manganese 1.17 silicon okay and carbon of 0.23. It is the same as a previous case okay but we just add about 30 ppm of boron then that can change the critical cooling rate significantly.

Because the boron creates the grain boundary and because of that you suppress the ferrite formation and due to that they know you in; you stabilized austenite and that austenite can be transformed to martensite upon cooling to room temperature.

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Microstructure before and after stamping

Top - before stamping, bottom - after quenching

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So, this is the microstructure what we talked about before hot stamping and this after hot stamping you start with ferritic pearlitic microstructure you end up with fully martensitic microstructure okay. So, the strength increases significantly and you do not really compromise in formability because you are forming at high temperature in austenitic region where material softened significantly in the austenitic region.

And you form it to make the component and you cool it and you form a fully martensitic microstructure and due to that this strenth of the component increases significantly okay.

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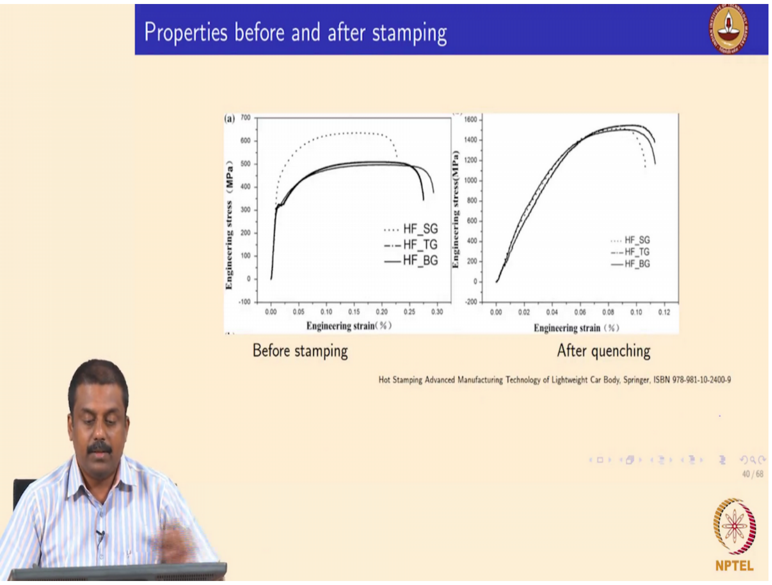

Properties before and after stamping

Before stamping

After quenching

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So, this is a properties after before and after forming and you start with the say ferritic pearlite microstructure yeah strength about 3 ma Pascal on UTS about say 450 that is what we saw in a previous in our banana diagram as well just it is a simple mild steel okay. And after forming you see ETS it went up to 1500 ma Pascal because of the formation of complete martensitic microstructure in the component okay.

So, you will see in the retail when you look at the weldability of these Steel's how the properties are affected okay.

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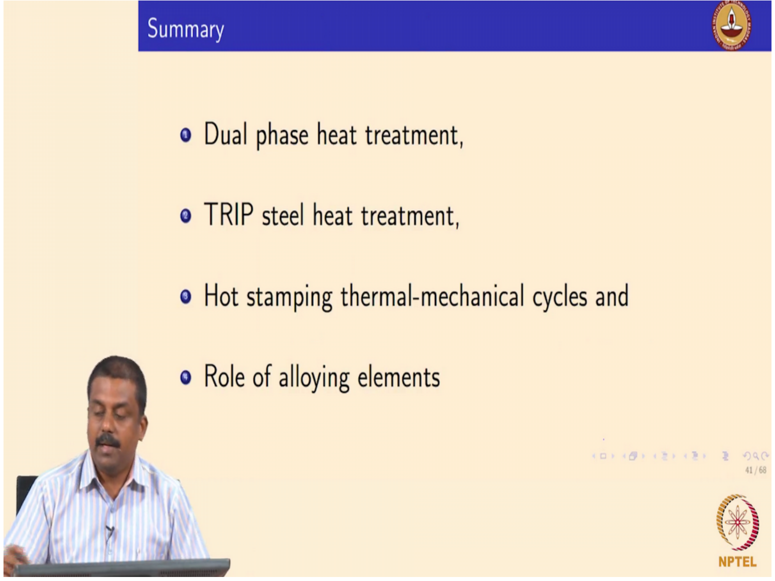

Summary

- Dual phase heat treatment,
- TRIP steel heat treatment,
- Hot stamping thermal-mechanical cycles and
- Role of alloying elements

So, to summarize this class so we looked at the heat treatments that are needed to generate dual phase micro structures, the role of carbon partitioning during inter critical annealing and how the carbon partitioning to the austenite can lead to martensite formation okay. And then we move on to trip steel microstructure how we get the trip three-phase micro structures right, ferrite carbon free bainite and the retained austenite containing micro structures.

Where we suppress cementite formation to enrich the austenite and because of the carbon enrichment the transmission of austenite to bainite ceases in completely the austenite carbon concentration reaches critical values known as T0 or allotropic phase boundary and these boundaries defined by the carbon concentration at a given temperature where the Gibbs energies of ferrite to austenite becomes equal.

And upon this constant concentration of austenite, the austenite can only transform to any other phase by diffusion less manner but is therefore it has to transform to martensite but what we do because of the enrichment your MS and MF temperature decreases significantly a muff goes below room temperature. So, therefore we stabilize the austenite which is untransformed during this isothermal bainitic holding as a retained austenite room temperature okay.

So, now and because of this special heat treatment we have a three phase micro structures generally we have a ferrite, carbide free bainite or bainitic ferrite and they retained austenite and we moved on to third steel which is hot stamping. And we looked at why hot sampling why we have to deform at higher temperatures. We looked at what is advantage of deforming or stamping in the austenitic region.

And what is the role of a alloying elements especially boron to obtain a complete microstructure complete martensitic microstructure apart from that and we also looked at the role of silicon aluminum and phosphorus in trip heat treatment.