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Dr. D. K. Dwivedi
Department of Mechanical and Industrial Engineering
Indian Institute of Technology - Roorkee

Lecture - 35
Metallurgical Transformations in Weld and Heat Affected Zone of Steels

Hello, I welcome you all in this presentation, this presentation is based on the topic Metallurgical transformations in the weld and heat affected zone of the steels. So now we will try to see that what are the typical features related to the weld thermal cycles determining the structural transformation in the weld as well as the heat affected zone.

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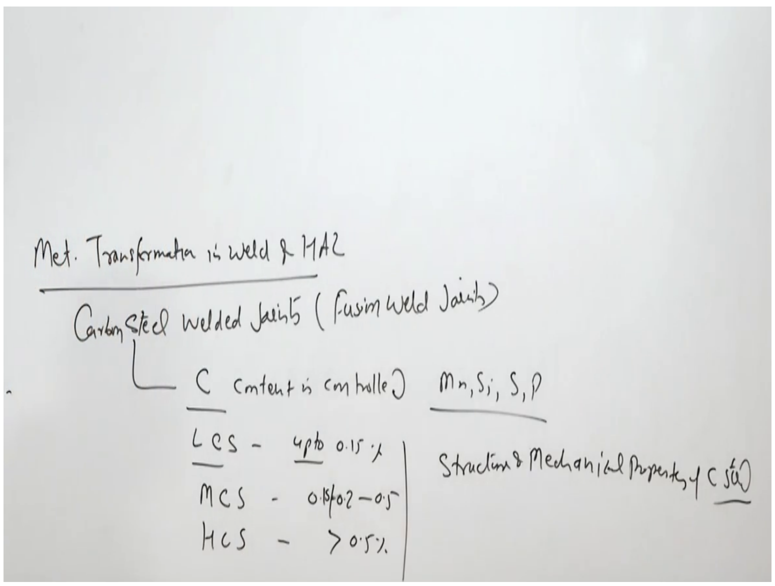

So the topic is metallurgical transformations in weld and heat affected zone especially in case of the steel - carbon steel welded joints, so basically we will consider the fusion weld joints in our this analysis, so we will talk sequentially a step-by-step the carbon steel is categorized when only the carbon content is controlled while the manganese, silicon, sulphur and phosphorus are kept as a residual elements.

And they are not expected to affect the metallurgical and structural properties of the steels significantly. So based on the carbon content these are categorized as a low carbon steels like say up to 0.15% in some cases it is used also 0.25% also, up to 0.2 also, medium carbon steels like say 0.15 to or like say 0.2 to 0.5 and high carbon steels like greater than 0.5%, so it is the carbon content that significantly determines the structure and mechanical properties - mechanical properties of carbon steels.

In general increase in carbon content increases the tensile strength that is the ultimate tensile strength and yield strength of the carbon steels, but at the cast of the ductility and toughness, so increase in carbon content up to the 0.8% there is a continuous increasing strength as well as hardness while there is a continuous decrease in strength and ductility is observed.

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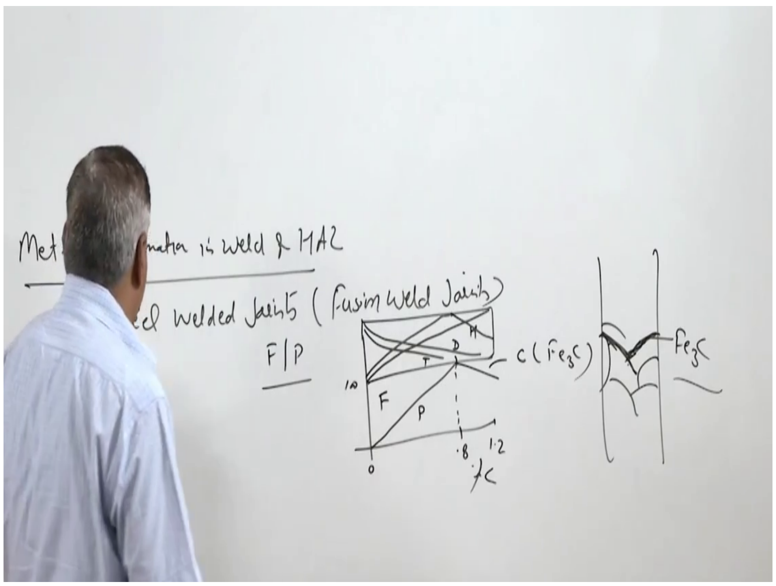

And this variation is attributed to the changing proportion of the ferrite and pearlite which are formed normally, if we will see like 0% carbon content 0.8% carbon content and 1.2% carbon content in x-axis and here is schematically if we show the structure in the first half say 100%, so here we start it will go in like this so here this shows the ferrite content when the carbon content is 0 the entire system is ferritic and the pearlite is 0.

When we go and with the increase in carbon content actually our pearlite content keeps on increasing and beyond this we start to see the cementite or which is Fe3C which starts appearing beyond the 0.18 that is the eutectoid point above which, so this change in the fraction of the ferrite and pearlite with the increase in carbon content is attributed to the changing properties.

So this changing properties is also can be shown is schematically here like this that there is a continuous drop in this strength and sorry toughness and the ductility like this say ductility and toughness there is a continuous increase in the hardness like this while the tensile strength increases up to the eutectoid point. And thereafter starts decreasing and this decrease is attributed to the formation of the cementite along the boundary of the pearlite that is a proeutectoid phase which is found along the grain boundaries.

So being hard and brittle say this is all these are the pearlite grains and when the hard brittle phases starts appearing along the boundary which is very weak in the strength. So Fe3 formation of the Fe3C network when it is in discrete inform reduction in strength is not much like this, but the significant reduction in strength takes place when the continuous network of Fe3C is formed, so basically in with the change in carbon content.

There is a significant change in the mechanical properties due to the changing proportion of the various phases which are being formed.

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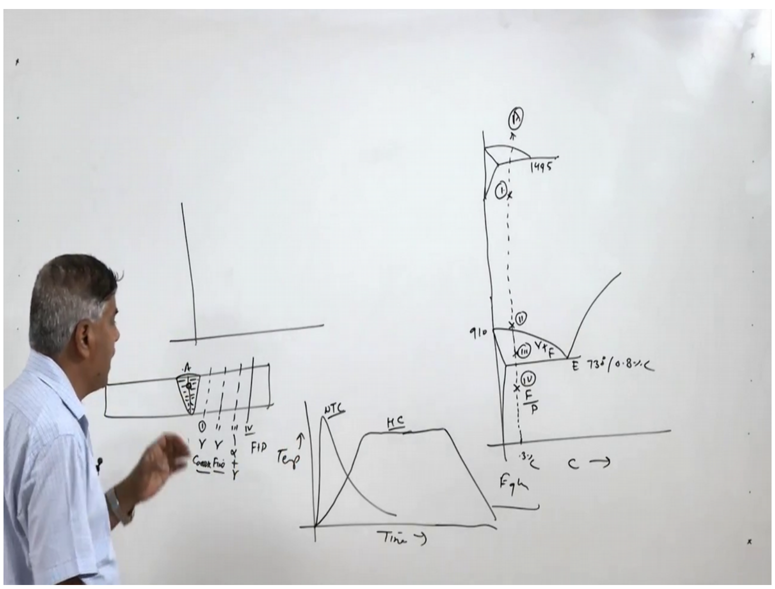

So in case of the carbon steel we see - we know that which kind of the phases which will be formed during the welding that will depend upon the kind of the weld thermal cycle being experienced by the different zones, so if we will see let us take this example where the two plates are being welded - are being joined by diffusion welding process, so the weld zone is produced from this metal is brought to the molten state and thereafter solidification proceeds.

So the - the there is one zone which is called this is the weld zone then there will be the different zones which will be experiencing the different temperatures, so consider here the three areas 1, 2 three locations 1, 2 and 3 at varying distance or increasing distance from the fusion boundary and there is one location A in the weld zone.

So all three locations will be experiencing the different temperatures and different holding times that is what we can see from the weld thermal cycles also for the different points, so if we compare - if we compare it with the Iron carbon diagram and TTT diagram so what will you formed under the different temperatures conditions, so for that what we have to see likes say iron carbon diagram will be seeing first.

So here this is over the alpha zone and this is the eutectoid zone and here what we have delta phase zone like this, so - so like here this is the eutectoid point which occurs 730 degree centigrade and 0.8% carbon content and if we take any steel corresponding to say 0.3% carbon steel we will be drawing simply a vertical line like this which will indicate the different phases which will be formed at the different temperature.

So this occurs at 1495 and we will see this is 910, 730 degree centigrade corresponding to 0.8% carbon content, so we will see that the - the system this will be having mostly the ferritic with the little amount of the pearlite, when it is heated what we get, we get the different points which will be experiencing the different temperatures. So with respect to the weld thermal cycle the point A which is in the weld zone will be experiencing the temperature greater than the liquidus temperature.

So let us say the point A location is this one and the point 1 which is very close to the fusion boundary will be experiencing much higher temperature. So the point 1 is this one let us take here and the point 2 is away further away where means above the further means - further away from the - away from the fusion boundary, but so it will be experiencing lower temperature let us take the point 2 is corresponding to this location.

And then point 3 is corresponding to this location right and like - like say the point 4 is this one which will be experiencing the temperature further below the 730 degree centigrade so this is point 4. So if we see - if we check the diagram what will be having this is the two phase zone, where we will be having gamma + pearlite, because all our during the heating first the pearlite will transform at this 730 degree centigrade into the austenite.

And so in this temperature band will be having the austenite + ferrite and as soon as temperature crosses about this upper critical temperature limit or a critical temperature line will be having mostly austenite. So the point 1 point 4 as the ferrite and pearlite point 3 will be having alpha + austenite means the ferrite + austenite and point 2 will be having just austenite and the point 1 will be having so this austenite will be fine one.

Because it is it will - it is kept at lower temperature it is experiencing lower temperature and the point 1 will be experiencing much higher temperature, so point 1 is again austenite, but it is very coarse, so coarse austenite. So as we approach there is a continuous change in the structure the base metal that is ferrite + pearlite then alpha + austenite + austenite, fine austenite and then coarse austenite.

These are the conditions which steel will be experiencing and under the equilibrium conditions, but not under the actual welding conditions. So if we compare the actual welding conditions they are slightly different how in which way they are different for that we need to see the weld thermal cycle which will be experienced by this points. So first compare the weld thermal cycle and the heat treatment cycles which are encountered, so well thermal cycle experiences much higher heating rate followed by the rapid cooling.

While in case of the heat treatment it experiences the lower heating rate and then it will be experiencing the lower means the steady-state followed by controlled cooling as per the kind of heat treatment which is performed, so exposure at high temperature is for much longer period the rate of heating and rate of cooling are slower as compared to the one which is experienced under the welding conditions weld thermal cycle.

And the heat treatment cycles are different in terms of the way by which the temperature variation as a function of the time takes place, so here in y axis we have temperature and in x-axis we have time, so the time is very short and the temperature is much higher, because a heat treatment normally is performed in the austenitic state of most of the steals. So the temperature here reaches up, even up to the fusion temperature and above that.

But the heat treatment is carried out normally in austenitic temperature band which is like say 50 degree 60 degree or 100 degree centigrade above the austenitic or above the upper critical temperature limits, so that is about say 900, 950 or maximum 1000 degree centigrade not like 1400 or 1300 degree centigrade. So but that the temperature experienced is much higher rate of heating and cooling experienced are much higher.

But the time of the retention at high temperature is limited in case of the weld thermal cycle, so this limited availability of the high temperature brings in the lot of heterogeneity in - in terms of the structure which is formed and that will be leading to the lot of structural variation and heterogeneity in the properties of the weld joint.

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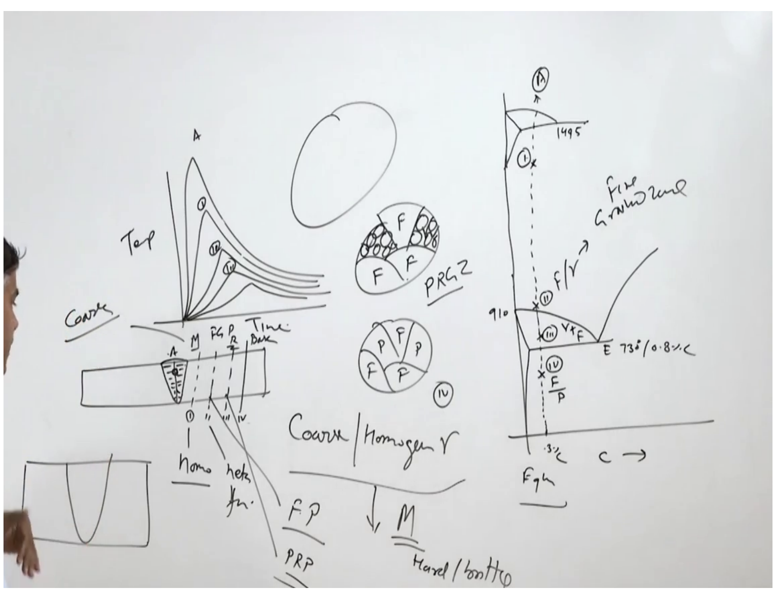

For example here as per the according to the weld according to the iron carbon diagram it should - it should be like at point 2 it should be the homogeneous fine austenite, it should be the homogeneous coarse austenite at point 1 and it should be austenite and the ferrite at the point 3, but since during the welding the weld thermal cycles being experienced at the different points are completely different like this say for point A.

So our peak temperature is reducing holding time is also shorter as heating rate is reducing cooling rate is reducing, so this is for say point 1, point 2, 3 likewise and 4 it will be further like this, so actually our weld thermal cycle if we see for correspond three different or different zones then we will be saying that point 1 experiencing the much higher temperature as compared to the point 3 and 4, then for point 2, point 3 and like this.

But it takes shorter period to reach there and longer time it takes for reaching at the lower temperatures at the points which are located further away from the fusion boundary, so considering these aspects if we see the lower cooling rates will be experienced by the point 3 higher cooling rate will be experienced by the point 2, further higher cooling rate will be experienced by the point 1.

So point 1 will have the coarse austenite which maybe which may have tendency for more homogeneous, but ill will be the heterogeneous austenite which will be fine also, so we know that the coarse and homogeneous - homogeneous austenite in case of carbon steels this promotes the tendency for martensitic transformation, so which is very hard as well as very brittle this is one typical case.

While the points 2 and 3 will be - point 2 which is located further away from point 2 is of the fine austenite, so fine austenite will be promoting - will be discouraging actually martensitic transformation will be promoting the softer phases like the fine pearlite - fine perlite or the bainite as for the cooling conditions.

So mostly it is fine pearlite which will be produced and in case of, at this point at the point 3 - point 3 wherever like say consider this one ferrite, ferrite, pearlite, pearlite, ferrite, so here this is the situation at the point 4 which is the base metal when we heated it to the point 3, so all our - all our grains corresponding to the pearlite will be transformed into the austenite.

So here this reminds ferrite, this reminds ferrite, here pearlite transforms into austenite, here pearlite transforms into the austenite, this grain again reminds the ferrite, so during the heating the point 3 will be experiencing the both ferrite + austenite and subsequent rapid cooling results in the transformation of this gamma into the fine pearlite, so what we will have basically this gamma will transform into the finer pearlite grains with in the austenite.

So this zone actually results in the formation of the partially refined - partially refined grain zone - partially refined grain zone while the zone 3, zone 2 results in the very fine grained - fine grained zone, so as for as the weld of the steel is concerned here we can see in case of the welding this may result in the martensite formation, then we will have the fine grained zone formation then partially refined grain zone formation and then unaffected base metals.

So we will see that continuous change in this structure here martensite but the coarse martensite then fine grained zone will have fine pearlite and the partially refined zone will have the partially fine pearlite, so there will continuous change in terms of the phases as well as in terms of the grain structure or the size of the grains, so these are the typical structural transformation which will be occurring in case of the low carbon steels.

Further if - if very heterogeneous austenite is formed where due to the lack of time the pearlite which is of the higher carbon content during the subsequent cooling phase of the welding high carbon austenite formed as a result of the transformation from pearlite to the austenite, so this will be resulting in the high carbon martensite also.

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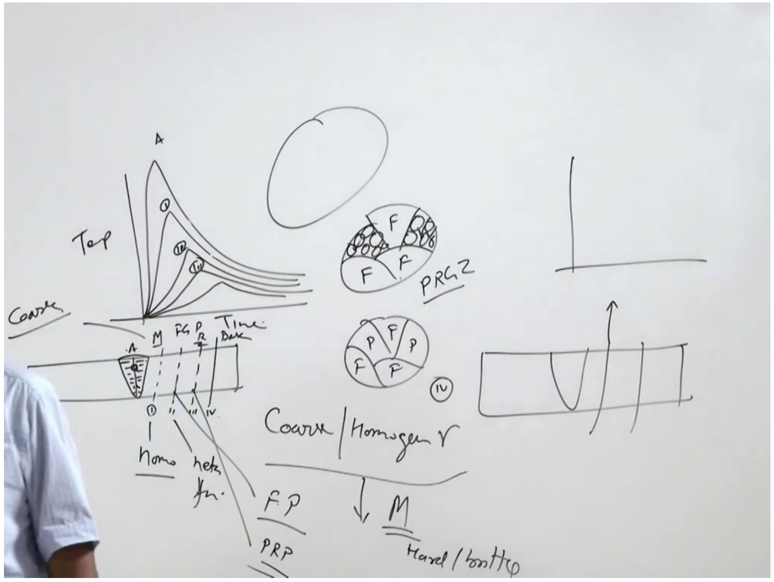

So if we see again another case like this the heat affected zone, so here in this area if we have if the weld thermal cycle is such that enough time is not available for homogenization of the austenite, so the and carbon is not able to diffuse equally in the entire mass to have the homogeneity in terms of the composition.

So whatever grains, whatever austenite has been formed due to the transformation of perlite into the austenite that will have the higher carbon content and during the subsequent cooling it will be forming the high carbon martensite, so which will result in - which will result in the lot of variation in terms of the hardness across the weld interface.

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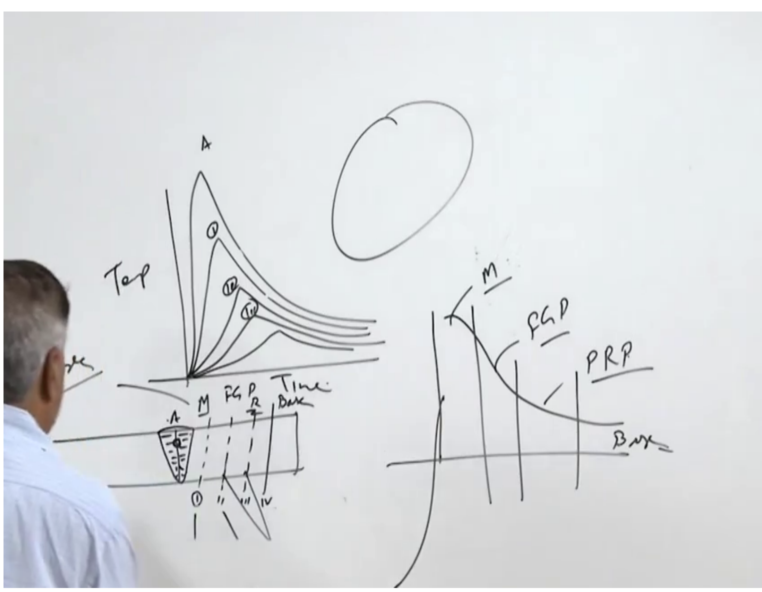

So in general if we plot the variation in the hardness as a function of the distance from the fusion boundary than typically in the weld joints in the simple carbon steels the variation like this is a fusion boundary what we will see that as a function of the distance from the fusion boundary we say this significant higher hardness and then hardness will keep on decreasing so this high hardness is attributed to the martensitic transformation.

Then finer fine grained pearlite, then partiality fine pearlite and then the base metal, so these are the three different zones which are formed coarse martensite offering much higher hardness as compared to the other areas, so these are the typical phase transformations which are observed in case of the carbon steel as well in the - in the heat affected zone.

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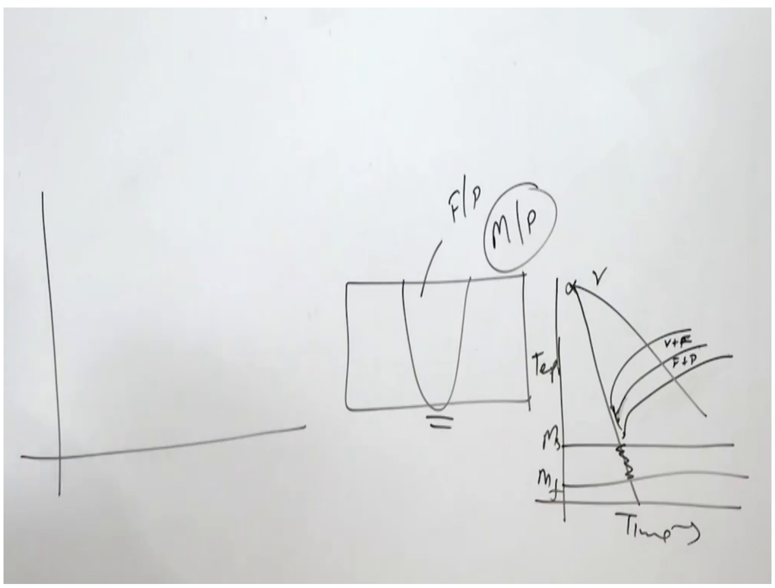

So far we have not talked about the weld, in general weld experiences the much higher heating rate as well as cooling rate and that is why as per the carbon content in the steel mostly it forms either ferrite or pearlite or it may form the martensite and the pearlite in the weld and that is what will be governed by the composition of the steel, so for that we need to see the CCT diagram for the - for that particular grade of the steel.

So if the CCT diagram goes in here like this, this is the proeutectoid phase like this so here our temperature, here we have time and this is our austenite at high temperature, so first on the during the cooling our under the slow cooling conditions austenite - austenite first transforms into the formation starts into the ferrite and then our remaining austenite transforms into the ferrite + pearlite under the conditions cooling when cooling conditions are somewhat low.

When the cooling conditions are really fast then it will be resulting in the transformation of the martensite - transformations austenite into the martensite, so and this formation will be occurring in this case, since the cooling conditions experienced by the weld zone in terms of the heating rate and the cooling rate are much faster as compared to the - the heat affected zone. That is why invariably either fine pearlite coupled with the martensite is formed or high carbon martensite is formed as per the carbon content in the weld zone.

Now we will see the typical micrographs which will be showing the different microstructures which are produced.

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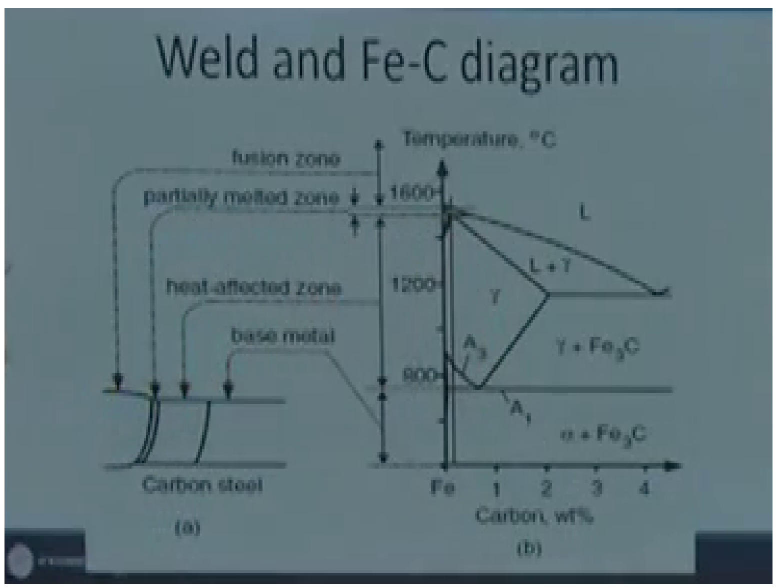

So here this is the kind of relationship for the weld zone, the zone next to the weld, the - the weld zone will be heated above the liquidus temperature and then the next to the fusion boundary there will be the two phase zone which will be falling - which will be falling between the liquidus and solidus and then will be having the heat affected zone that is the below the solidus and above the upper critical temperature zone.

And then we will have the base metal and the base metal will be the low - will be below the lower critical temperature, so this - this is the kind of relationship means the - the formation of the different zones and their relation with the iron carbon diagram.

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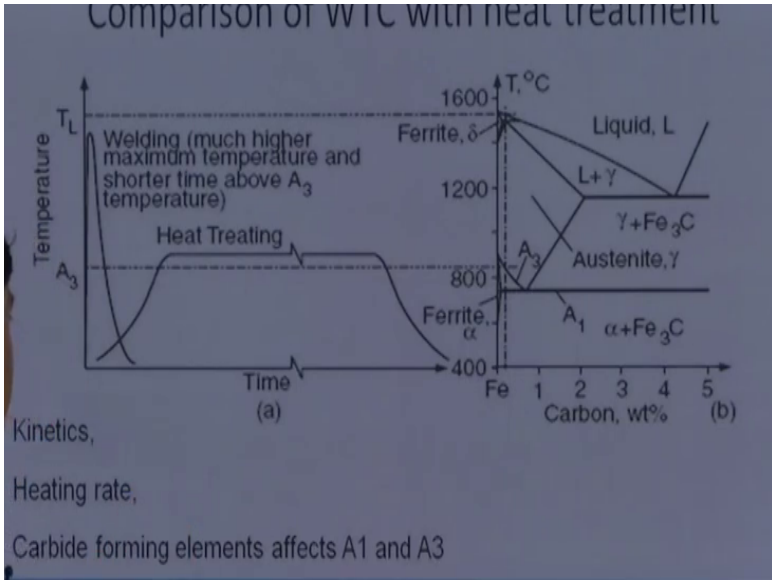

This is what I have already explained that, there is a lot of difference in terms of the weld thermal cycle and the heat treatment cycles which are used for the two cases.

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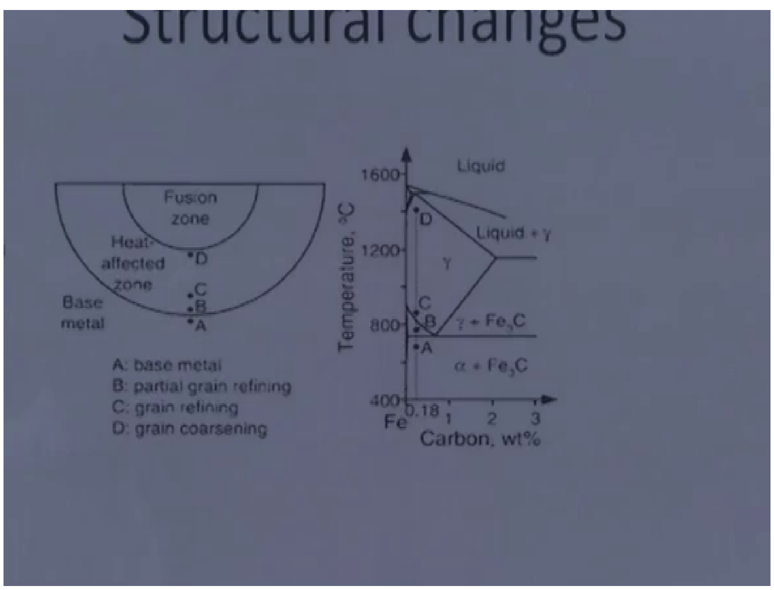

And this is what I have already explained like say if plate weld is made then the weld fusion zone is this one which will be experiencing the temperature above the liquidus and the next to that there will be heat affected zone which will be experiencing much higher temperature for longer period, that will be the point D and point C corresponds to the just about the upper critical temperature, point B is in the two phase zone and point A is in the base metal.

So accordingly the point D will be experiencing the coarse grain coarsening and in form of austenite and subsequent rapid cooling results in the coarse martensite, C will be experiencing the fine grain refinement especially in case of the and this will result in the fine pearlite and partially refined zone will be experienced by the point B which is in the two phases zone. Basically it is the integral – inter-critical zone falling between the upper critical.

And the lower critical temperature lines and the base metal is the A as per the composition it will have - it will have the different phases.

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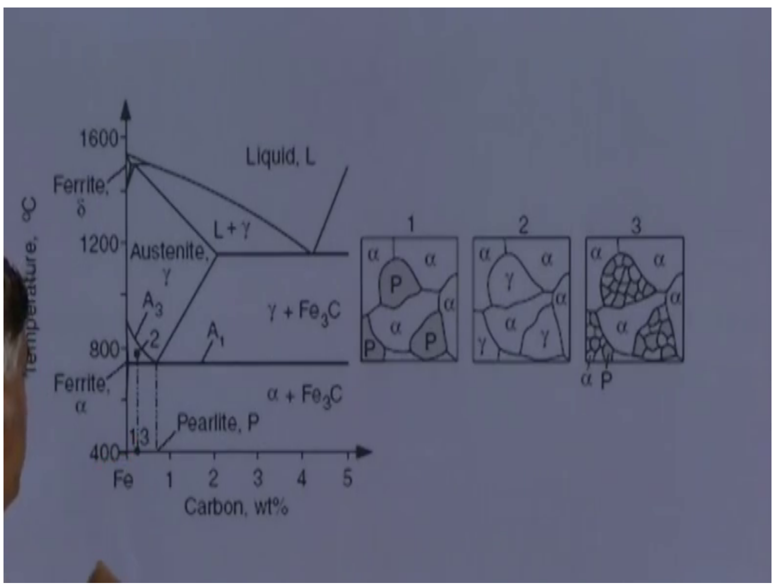

So if we will see that the base metal say typical steel say corresponding to the 0.3% carbon steel at 1 and 3 what it will have at the point 1 it has the ferrite and pearlite, so the ferrite alpha and pearlite these are grey color, the grey shaded areas when it is heated to the point 2 then the pearlite will transform into the austenite while the alpha will remain as it is, so all pearlite grains will transform into the austenite.

And subsequently rapid cooling in case of the welding results in the fine pearlite and the ferrite grains, fine pearlite and the alpha grains remains as it is, so this results in the partially refined zone, because our austenite ferrite grains remains as it is and only the pearlite grains are refined due to the heating between the inter-critical zone.

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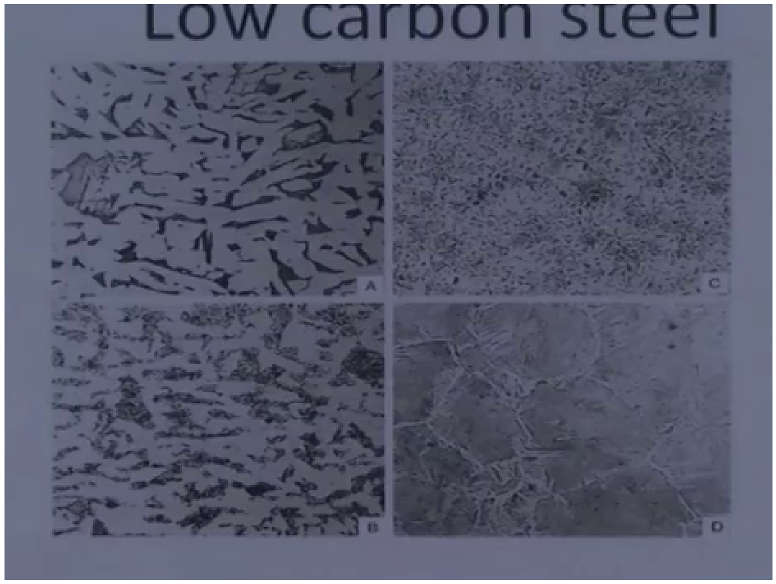

And this is what the actual diagram shows in the - the base metal having the - the light touched white ferrite ferritic grains and the dark edged the pearlitic grains when they are heated to the point 2 like this one heated to the point 2 and then cooled rapidly then it results in the partially refined zone.

So all ferrite grains are as it is and whatever pearlite grains where there they reached to the - they converted into the austenite and rapid cooling results in the formation of the fine pearlite the point 3 experiences point 3 like say heating up to this location as I have explained earlier the points 3 will be in the zone C is just above the upper critical temperature, so all the austenite, all the ferrite and pearlite will transforming into the austenite and austenite that too very fine.

So it will promote and during the subsequent cooling phase of the weld thermal cycle it will be promoting the fine pearlitic grain structure and the point B, point D means when it is heated point D is here with the - the - the location - this location very close to the fusion boundary and it is heated to the much higher temperature for longer period that is why it experiences grain coarsening very - very coarse it results in the formation of very coarse austenite.

And coarse austenite during the subsequent cooling promotes the martensitic transformation, so the coarse grains we can see this corresponded to the coarse of austenite and subsequent cooling will be resulting in the martensitic transformation, this is low carbon steel system so all martensitic - all martensitic transformation can be seen along the grain boundaries and remaining are the ferritic ones.

So this is how we can see in the in case of the carbon steels the heterogeneity of the weld thermal cycle results in the lot of changes in the structure ranging from the ferrite, pearlite in the base metal to the partially refined pearlite in the partially refined grains zone and fully refined pearlite in the refined zone.

And then coarse martensite is formed next to the fusion boundary which is heated for much higher period to the much higher temperature for longer period that is why it promotes the martensitic transformation also, so which type which what will be the phases which will be formed that will depend upon the carbon content, high carbon steels invariably form the martins invariable invariably forms the martensite in the heat affected zone.

That and that is why it causes the embrittlement or the loss of toughness of the weld joints and that is why to avoid the - the losses of the toughness and the ductility, the tempering of the weld joints is invariably done, so that the - the toughness can be induced so means heat treatment is done so that toughness can be induced and also the relative residual stresses can be reduced. So thank you for your attention.