Principles of Physical Metallurgy

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Lecture No. # 23

Iron – Carbon Phase Diagram

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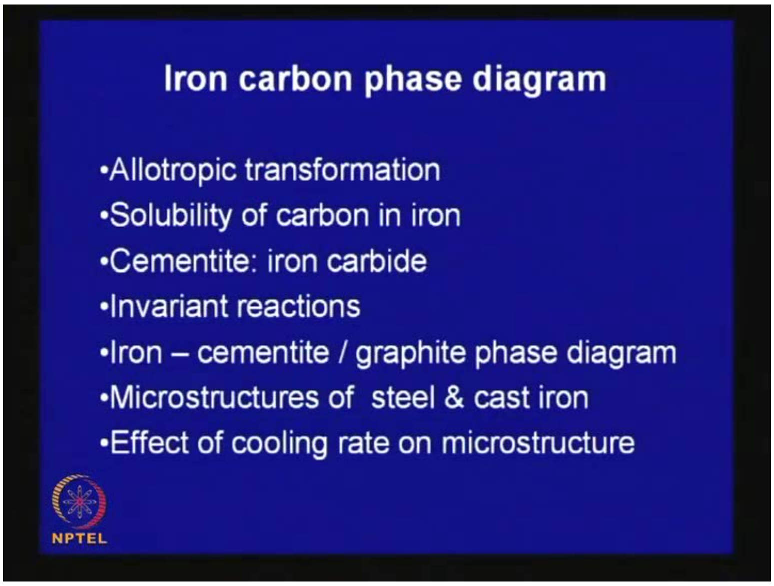

Good morning, last five classes we talked about process of solidification, and particularly with reference to I mean in general, I mean two hypothetical metals a and b, and how the solid, how the solidified form a metal. And how do you interpret it is structure, and what is the effect of composition on the structure, and we also talked about several invariant reactions. But all these were discussed in general using hypothetical cases.

Today, we look at one specific phase diagram that is called iron carbon phase diagram, and we will see that with iron with carbon forms a compound called carbide, that is iron carbide which is known as cemented. And in fact, the first diagram that will talk about is actually iron, iron carbide phase diagram; and this forms the very basis of or describes the formation of the structure or one of the most commonly used material by human being, that is steel.

And let us see that under this chapter that is iron carbon phase diagram. We will look at that allotropic transformation iron exists in several crystalline forms, and carbon can dissolve in this lattice of iron, and this solubility is a function of crystal structure and temperature. And we also will talk about a cementited phase which is iron carbide, it has a definite competition and because of the limited solubility of carbon in iron, and in the iron carbon phase diagram we do get several invariant reactions, we will look at them. We will look at iron and cementited phase diagram, it is start with later on we will also talk about, that iron graphite phase diagram, because graphite is the most stable phase of carbon and …

So, how this diagram does change when cemented down to graphite we will also talk about, the evolution of microstructures in steel and we will know about the difference between steel and cast iron. And we will have a passing comment on effect of cooling rate, although the equilibrium diagram just describes the structure evolution under very slow rate of cooling nevertheless we will see that how this gets change with the how do we take into account effect of cooling rate on microstructure.

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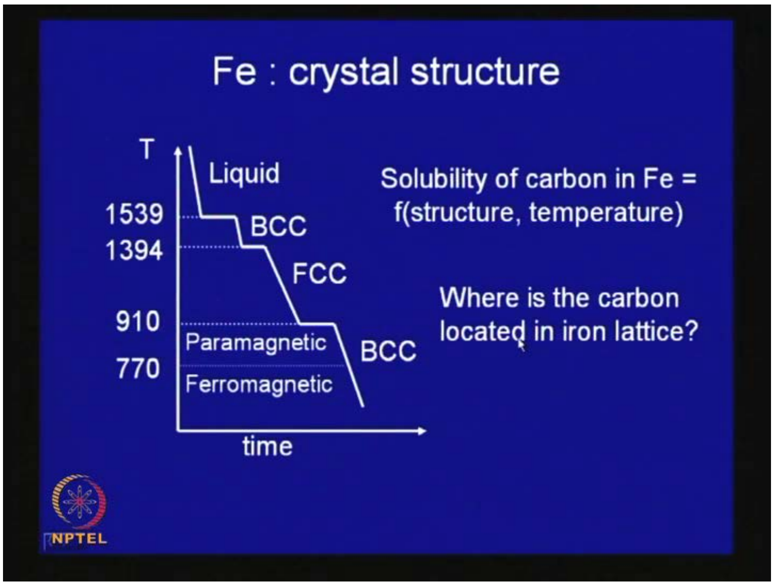

Now, if you look at say suppose if you take molten iron or take iron in a crucible melt it heat it to let us say 1550 degree centigrade. And then you let it cool very slowly, and measure the temperature. And if you measure and if you make a plot of this temperature as a function of time, you will find that the cooling curve you will get a number of steps.

These steps represent equilibrium between the liquid say this one; first one between liquid and solid. And this here step represents the equilibrium between two solid phases, and this also represents equilibrium between two solid phases. So, the transformation that it goes through is first it solidifies the liquid solidifies into a crystalline structure and it is body centered cubic, next at a little lower temperature so this 1394 this body centered cubic structure gets converted in to face centered cubic structure; again this face centered cubic structure it is converted into a body centered cubic structure.

So, you have a high temperature BCC structure you have a low temperature body centered cubic structure. And if you cool further below that initially that BCC structure this does not exhibit magnetic property this paramagnetic. It is and if you cool below a temperature called curie temperature that is around 770 degree centigrade below this; it is ferromagnetic in nature, but here it does not have any I mean any other than changes is negligible so therefore that you do not get any step here, but if you measure magnetic property, you do find a change.

So that way you can say as you heat iron from room temperature to its melting point. It will convert from ferromagnetic state to paramagnetic state at Curie temperature, then from paramagnetic basis crystal structure it gets converted into a face centered cubic again at 1394, it get converted into a body centered cubic structure, and then melting takes place at 1539. Now, the solubility of carbon and if you add carbon of course, this cooling curve will change. And how does it change; this will depend on the extent of solubility of carbon in iron; and this solubility depends on the crystal structure as well as the temperature. As the question comes where is the carbon atom located if dissolves in iron, where will the carbon atom go and this is shown in the next diagram.

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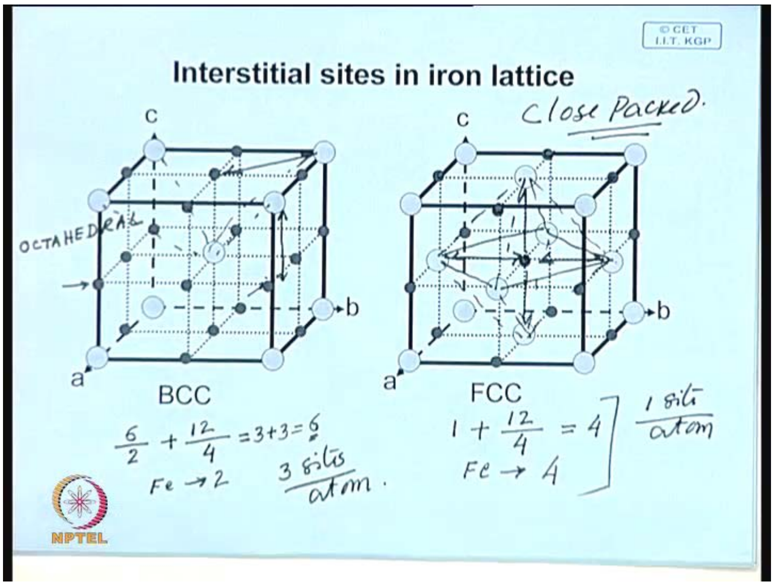

So this is a body centered cubic structure. If it is a body centered cubic structure; then I am in this large spheres they represent location of iron and atom. So, this is a BCC structure so you have one atom at the corner of the cell, at the centre of the cell and with these red dots this location of interstitial sites have been represented, say this they represent possible locations where a carbon atom can go. So, these in a BCC structure if you recall your earlier lecture that the atoms touch their arrange in such a way that along the diagonal direction the touch each other. And we did calculate the dimension of the interstitial spacing's, so here you will find that interstitial the gap these sites they are called octahedral sites. And octahedral sites then if you if you look at this paper here, these are called octahedral site octahedral sites and you see the one-dimension see is in this direction.

So, we can see one-dimension is this direction this gap is much smaller; than the gap in this directions. So, they are called identical site, if you join these and similarly if you visualize there is another on the top and you can join these with the center atom on the unit cell. Above this, then you will get an octahedral and that centre of that octahedron is the likely location of carbon atom. And here, if you found that number of sides you will find that you have 6 faces. So, each face is here by 2 unit cells so contribution of this face centre it is 6 over 2 and then you also have edges and you have 12 edges, so 12 edges, but each edge you can have along each edge you can have 4 such unit cells.

So, contribution of this is 12 plus 4; so this comes out to be this is 3 plus 3 that is 6. And BCC lattice you have 2 atoms per lattice. So, you have lightly interstitial site is 6 per unit cell and iron atom you have 2. So, everyone iron atom you have three interstitial site whereas, if you look at face centered cubic structure here also these are called octahedral sites which are the centre of the edges and here, if you try and join and make this octahedron so, you look at; so this is the centre of the octahedron; you have this is the centre of that octahedron you can join. And similarly, you can join this get an octahedron, but the difference here this octahedron it is seen, I mean this is a regular that this dimension of in this direction, and this interstitial gap in this direction they are identical.

And here, if you try and calculate the number of interstitial site what you have? You have one at the centre, and you have 12 centres of 12 edges and for each edge an each edge you can have 4 unit cells so it is contribution is one-fourth and this will add up to 4. And in FCC lattice you have 4 iron atoms per unit cell so here you have one atom or one site per atom. Here, you have three sites per atom so obviously; even though we know that BCC structure is not as close packed as face centered cubic; face centered cubic this is also called close pack structure, this is as the maximum packing density close pack structure; this has maximum packing density, but although the packing density is higher the gaps; whatever you have those gaps are larger, because you have one site per atom and here you have three sites per atom.

So that gap even though, you have total void space is more here that gets distributed among more number of sites so that is why, here true that you have more open space, but the dimension of the space the shortest dimension if a carbon atom goes here, it will push up unless these atoms are pushed apart; it may not be able to move into the site so that is why, in BCC the solubility of carbon is very limited whereas, in face centered cubic structure the solubility of carbon is much higher. And so this is why you know; you will have as you cool as solidified metal initially if even if BCC structure has formed. And later on when it converts into FCC, it can accommodate more number of carbon atoms so there will be some kind of transformations, which will involve which may involve 3 faces.

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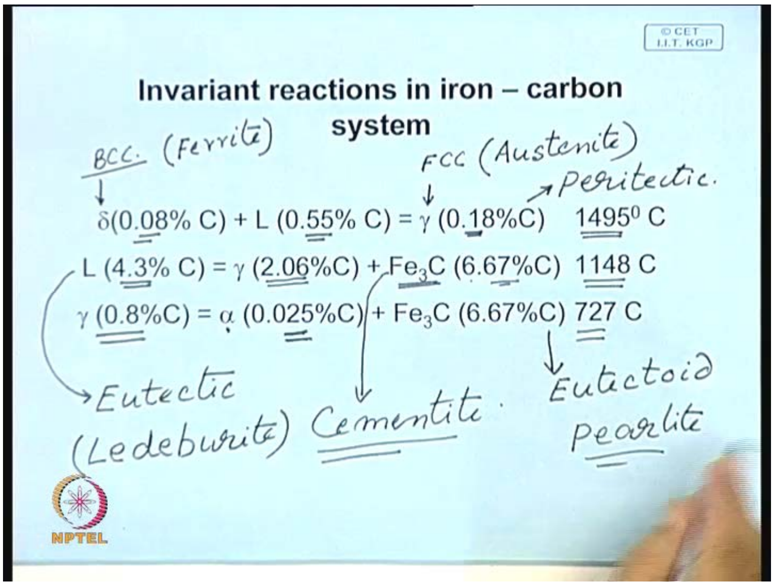

And therefore, what you have in the iron carbon diagram, you will have three invariant reactions which are listed in this slide. So these are the three invariant reactions; so, you have look at here, the delta phase delta is BCC, and phase if I look at it here, this is the first face which comes out this is body centered cubic. And here, this delta reacts with the liquid, and will give you austenite this is called gamma, this has faced centered cubic structure, and these are very commonly known as the solid solution is commonly known as austenite. And BCC structure is known as ferrite, and this is called delta ferrite; this is the high temperature form of being body centered cubic iron.

So, this you can say that this is delta ferrite, so this is austenite and this three face reaction is takes place at 1495 degree centigrade. And this reaction if you recollect your lecture. So, here this liquid reacts with solid giving another solid and mark here that carbon contained is fixed here this is a three faced equilibrium so they will have definite composition. So, now, here looks at it here gamma it has much higher carbon content than that of ferrite, so this is because; it can dissolve more amount of carbon. And this is weight percentage and this reaction is called peritectic reaction isotherm and next at a little lower temperature at 1145.

There is another reaction taking place; this is that liquid having a fix carbon That is 4.3 percent carbon definite carbon content breaks down into mixture of two phases this is gamma, which is called austenite. And look at it, here carbon content is around two percent and a carbide which has a definite composition is F e 3 C iron 3 atom a 3 atoms of iron. And one atom of carbon F e 3 C this is carbon content comes out to be 6.67 percent carbon and this is called cementited. This is F e 3 C is called cementited and this reaction is eutectic reaction, this invariant reaction is eutectic reaction. And product is eutectic and this product also has a definite name; that eutectic is iron carbon phase diagram it is leveled as or it is known as Ledeburite.

This will be an intimate mixture of austenite and cementited. And the third reaction, which takes place around 723 or 727 around this temperature, is a fix temperature. Here, the prostenite of a definite composition that is 0.8 percent carbon breaks down into a mixture of ferrite and cemented look at this ferrite; this has even lower carbon content than this; so, this is at a high temperature at a higher temperature lattice parameter also will be larger.

So, it is atomic command interstitial gap is also higher. So, here the solubility is little less, but look at the solubility here in ferrite this is the low temperature ferrite this has the body centered cubic structure. And here this austenite of 0.8 percent carbon breaks down into a mixture of ferrite and cemented. And this reaction is called a solid breaking down into a mixture of two solid. So, this is called this reaction is called eutectoid reaction, and the product that we get this type of structure that is known as pearlite.

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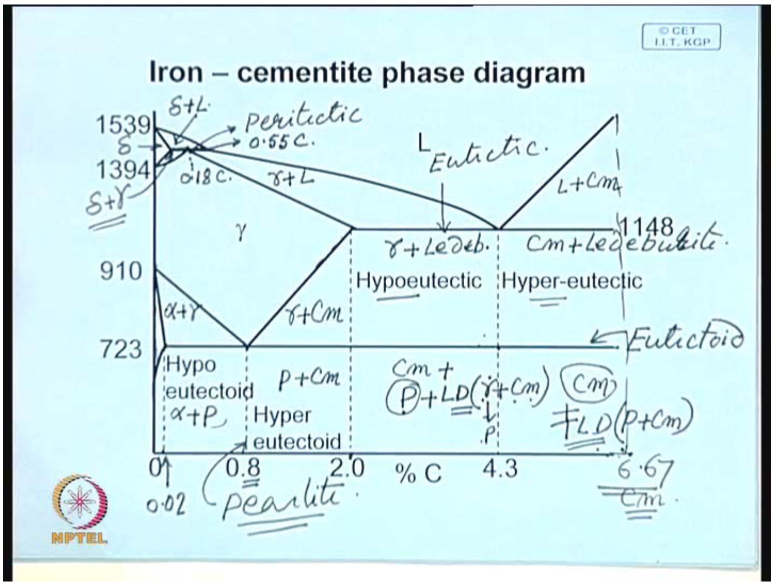

And now, let us see with this information how can we construct that phase diagram which is shown here; so, this is that paratactic reaction so here you have this is the region which is delta here.

You have liquid delta plus liquid, and delta plus liquid reacts here, this is the peritactic reaction isotherm; this is the peritactic reaction isotherm; and here, this is 0.808 percent carbon. And then this reacts with liquid; this has let us a 0.55 percent carbon and then it gives austenite of this composition which has 0.18 percent carbon. And here, when this reacts you get gamma and if it is on the other side right hand side of this you get gamma plus liquid; that means, here if it is on the right hand side amount of delta which has precipitated out amount is so less.

That even if it reacts with liquid the entire liquid is not consume some amount of liquid is left. And that remaining liquid solidifies into austenite whereas; on this side amount of gamma so large delta is large amount of on left hand side of this peritactic point amount of delta. So, large that entire liquid gets consumed and what you have here, in this region you will have delta plus gamma forms, but some amount of delta remains. So, likewise this part you will have this is the gamma plus liquid and this side you will have liquid from liquid cemented will precipitate out; and this cemented let us say this is composition this diagram this represent 6.67 percent carbon.

So that means, this line represent cemented; and this is called this isotherm is called Eutectic. And same terminology is followed on the left hand side of the eutectic; that alloys called Hypoeutectic on the right hand side of the eutectic, composition alloy is called Hypereutectic. So, here this part your structure will be gamma plus Eutectic; so this Eutectic is known as Ledeborite; and this side you will have primary cementited plus Ledeborite that is eutectic. Now, what happens on this side, this side gamma.

If you cool here, at this temperature that is around 723 degrees centigrade this is the other isotherm; and this isotherm is this is the Eutectoid isotherm. And here, that gamma here reacts and we give you, and will give you a Eutectoid structure; and this Eutectoid structure we said is called pearlite; and the alloy on the left hand side here, until this point is called Hypo -eutectoid, and the alloy from right hand side of this is called Hyper eutectoid. And in this case the structure will be that you can as gamma. Here, it gives you pearlite structure here, from gamma some amount of alpha will precipitate out.

So, this alpha is called which precipitates out before Eutectoid temperature is called Eutectoid alpha. Similarly, on this side from austenite as you cool here you will have cementited, so at room temperature between and this maximum solubility this is around 0.02. So, between this and this you have Hypo- eutectoid still where, the structure will be ferrite plus pearlite. And here, the structure will be pearlite plus ferrite Eutectoid cemented. And here what happens there is austenite here as you cool now. This austenite composition also will follow will change, and this change will be given by this line this represents solubility of carbon. In austenite as the temperature goes down the solubility a decrease. Now, here just before this Eutectoid reaction.

Now, you have certain amount of Ledeborite which is a mixture of austenite and cemented. And what happens here that austenite in Ledeborite will transform into pearliest. So, what you will have here, you will have some pro eutectoid commentate. When these because the solubility of carbon decreases some amount of cementited will precipitate out from austenite. Then you will have that entire austenite, whatever remaining austenite will convert into pearlite. And, then you have Ledeborite structure is represent Ledeborite is an LD. And which is a Ledeborite before this, it was a made up of before Eutectoid reaction it was made up of austenite plus cementited.

So, what happens these austenite; from which some amount of commentate will precipitate out as you pull down from here down ward and balance austenite will again convert into pearliest. So, what you have at room temperature is called transformed Ledeborite see where, which will be made up of a relatively intimate mixture of pearlite and cementited similarly on this side you will have cementited. And then you will have Ledeborite which is transforming transformed Ledeborite. So, which will be made up of pearlite plus cementited.

So, this gives you know this diagram therefore, gives you a picture of what type of structure you are likely to get at room temperature in an iron carbon alloy; as you increase amount of carbon. Let us say from very small amount and very large amount on when it is nearly 0; it will be pure ferrite say like. Here, say single phase structure and when it exceeds a particular amount you will get some amount of pearlite ferrite plus pearlite. Then when it exceeds 0.8 percent carbon, it will be pearlite plus cemented when you go beyond this two percent; then you will get the transformed eutectic also will appear transformed eutectic. And some amount of austenite which has been transformed into pearlite, so this is the type of structure and here you will get cemented and transform Ledeborite.

So that means, as carbon contains this change from 0 to 6.6 you get a significant change in the microstructure from pure ferrite; that means, pure iron to an extreme case that is iron carbide.

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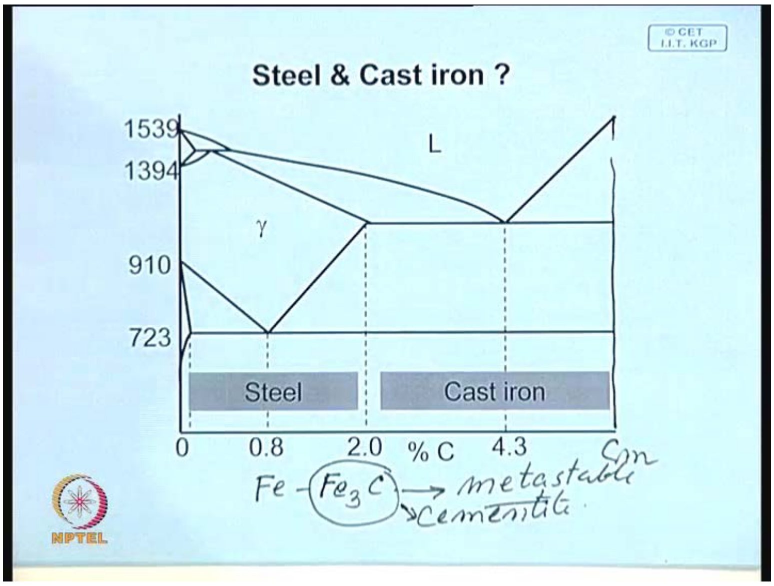

So, this diagram if you look at this is the phase diagram, and here what we say this alloys which are containing up to 2 percent is usually said, where you do not get any eutectic structure. This part of the diagram we call steel this represents a composition of steel, whereas if you go beyond two person this portion of the diagram represents cast iron. As we will go by we will see this type of cast iron, where you have substantial amount is known as light cast iron. And later on, we will see that assume increase the carbon content in the alloy the stability of that cementited decreases, and it can get converted into decompose into iron and graphite.

So that time you know the diagram will change slight slightly. And we will come to it little later, but let us for the time being concentrated on this particular type of diagram. This is also known as iron cementited phase diagram or you can say this cementited phase here. This diagram this represent cemented at is also known as Fe Fe 3 C carbon iron carbon phase diagram. And this which say that, this is a phase which is called meta stable phase. It is crystalline it has a complex cubic structure with a very large number of atoms unlike pure metal where, BCC you have 2 atoms per unit cell here; you have large number of atoms per unit cell. It has a little complex structure, but these are going to the details of that this is behavior wise its behavior you have melting characteristic exactly like a pure compound.

So, we can say this is a some kind of a compound like in a structure and we call this cementited.

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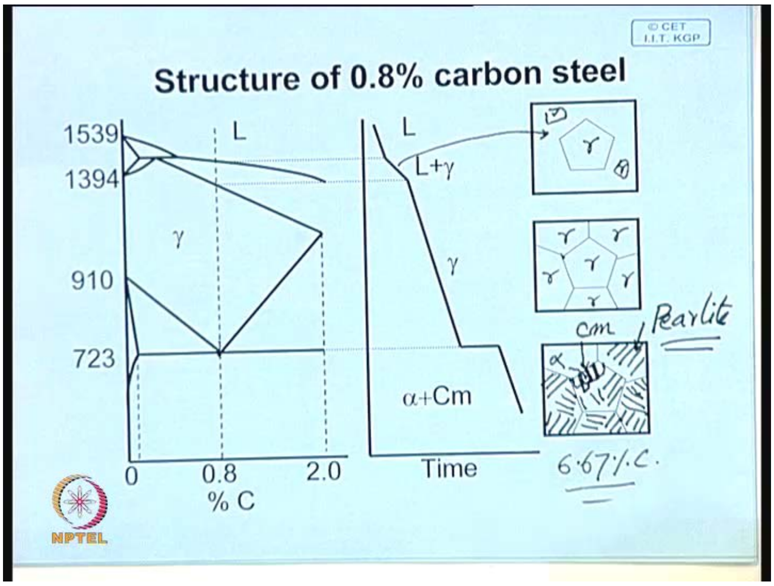

Now, let us look at the structure that you get when you cool an alloy containing 0.8 percent carbon. And this alloy is called a eutectoid steel or this iron carbon alloy steel is called a Eutectoid steel. And how what will be its cooling curve looking at this phase diagram it is very easy to construct its cooling curve you get an inflection here. This is the region where solidification takes place at from liquid gamma precipitates out here, solidification complete you have gamma and at this you take twice isotherm. This gamma decomposes into a mixture of ferrite and cementited let us see what will be its capture look like now here.

Let us say in this particular case as a solidification proceeds you will have gamma precipitating out you will some gamma here also gamma some precipitating out. And finally, it will be entirely filled up by gamma all these are gamma grains austenite grains. And now, at this temperature what happens say suppose you cool it slightly what happens here, first some carbide may precipitate out let us say suppose we see some carbide precipitating out here like this is a carbide precipitating out and carbide takes out very large amount of carbon this is 6.67 percent carbon. So, the surrounding region will get depleted of carbon so when it gets depleted another plate very low carbon area will form.

So, this is cementited let us, say the dark line is cemented white area this is ferrite that bright area is ferrite. And this how when this area ferrite precipitates out from this carbon will get rejected and it gets rejected is goes to the interface. And here, again plat elite of cemented nucleus this is the way the process continues and ultimately what you will find you will get this kind of the entire area it gets converted into this type of Eutectoid structure; so, this is called this type of structure is called pearlite laminar structure and this is shown pictorially here.

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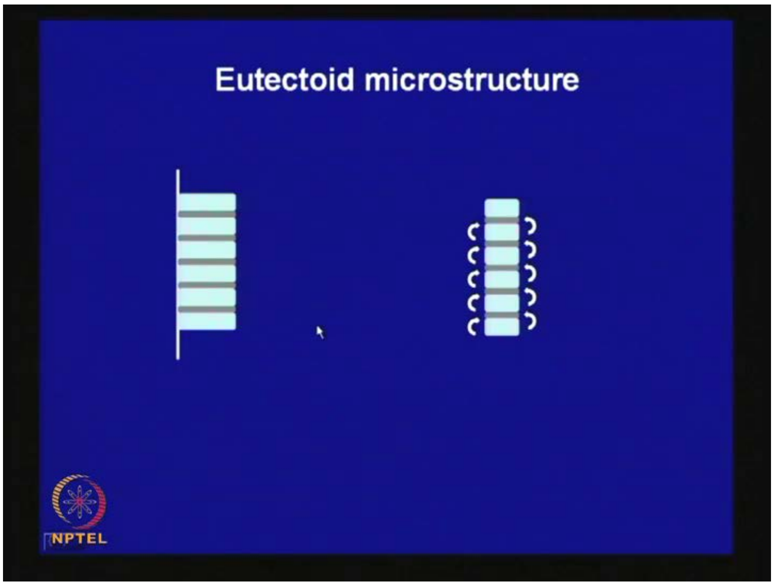

This is shown the mechanism when a plat elite of cementited, yet, it takes a lot of carbon from the neighboring area. So, this area the carbon gets depleted by plate late nucleus and this is the way progresses and this shown here some like this.

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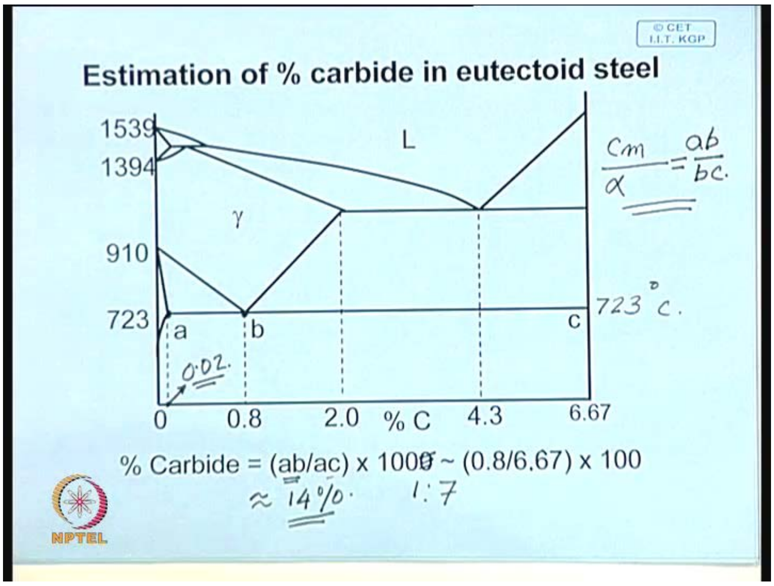

This is how the paralytic structure develops, now, we have seen phase diagram that it is possible to calculate the amount of phases which are present in the structure suppose here, you have cooled below this eutectoid temperature let us say 723 degree centigrade. Then what will be the amount of percentage carbide in this structure. Now here, you can apply lever rule that amount of just below this eutectoid temperature that you can say the amount of cementited will be proportional to this part that is cementited over ferrite this will be proportional to the cementited is proportional to this area. That is a b ferrite part proportional to this area that is b c this is the lever rule, and if you recollect the lever rule you can apply and try and find out what is the percentage carbide here.

So, this will be a b and if you neglect this if you say this is 0.02 for tactical purposes. If you, neglect this then you can see that this amount will be amount of carbide will be a b by a c in 100 percentage if you want to calculate this time hundred this will be around 0.8 over 6.67, and you can calculate it out and it may come around 14 percent.

So, if you look at that microstructure what you will find and this microstructure. This type of paralytic phases that structure you will find that around approximately. This is comes out to be 14 percent and say you can say 1 is to 7, and if you make an assumption that density of ferrite and carbide they are nearly same.

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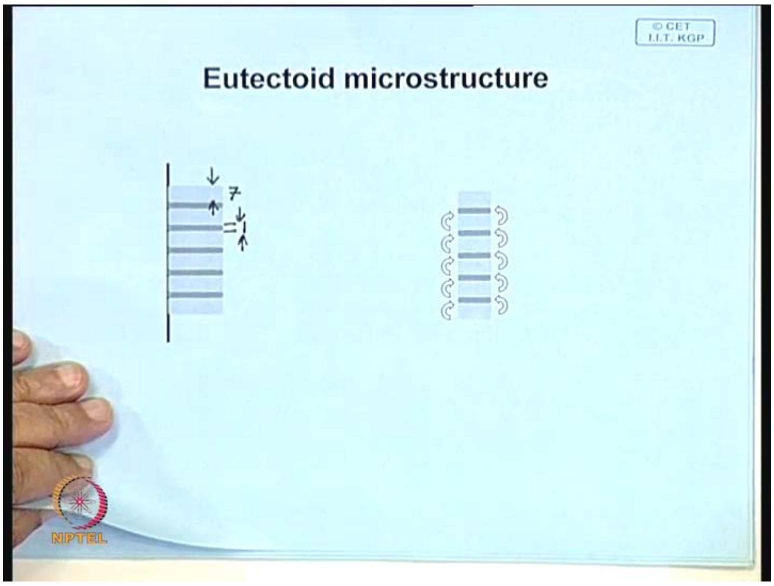

So, this will also represent the volume percentage and volume percentage is what when you see when you look at the micro structure. So, this part this is the width of ferrite plate so this is 7 this width of cemented plate will be around 1 is to 7 so you get laments power that mean pearliest microstructure. So, laminar structure two phases are present in the ratio 1 is to 7.

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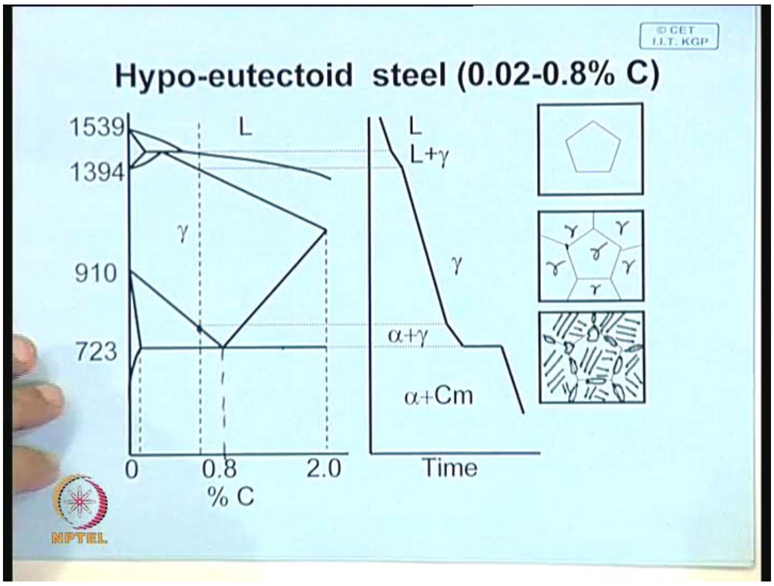

So, in the same way I leave it to you to find out the microstructure will develop for a Hypo- eutectoid steel anything between 0.02 to 0.8 this you can clearly see that here.

Apart from that, you take in the Eutectoid structure; you have some amount of ferrite precipitating out as this which are the at the temperature zone from here to here; that means, this is a critical temperature say where from austenite some amount of cementited will get richer in carbon and austenite composition will change along this line. Until you reach that you take this isotherm where you will have ferrite would virtually know carbon. And another you have austenite where you will have another carbon that is around 0.8 percent carbon so here what you have is this is the point.

So; that means, over here until this you have this type of structure you have veins of austenite and here you will have when this temperature goes below this you will have some ferrite doing in the boundary. So, you will have some ferrite doing nuclear here a grin boundary these are the pro Eutectoid ferrite and when that the eutectoid temperature is reached you will still have some amount of austenite left and the balance austenite we will transform into paralytic structure so you will have this kind of microstructure.

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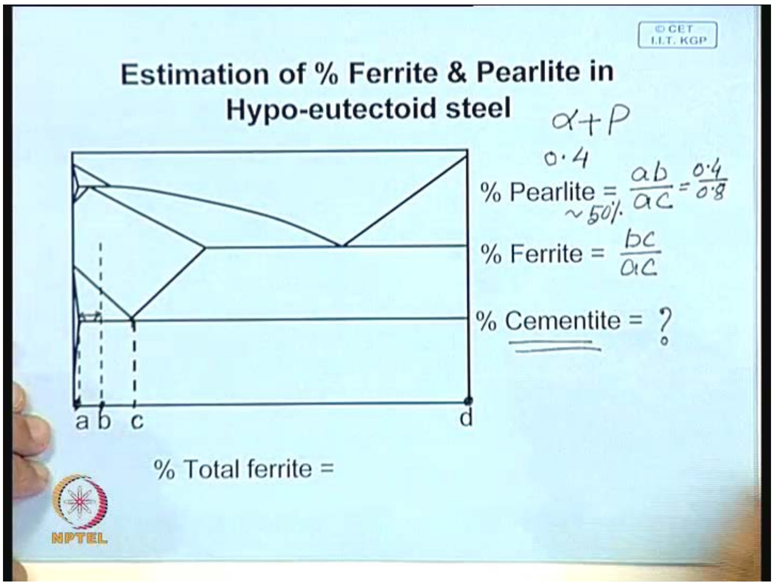

So, this is the case of hypo eutectoid steel and in the case of a you can do an estimate now you can also estimate here just now the estimated amount of cemented in a Eutectoid structure. So, here in this structure say if this is the composition and here, you have a structure will consist of ferrite plus pearlite. How do you find out percentage pearlite has 0.8 percent carbon. Which is represented by point c and here? So, therefore percentage pearliest will be equal to pearlite amount of pearlite will be proportional to this region; so, that means, a b and this entire region is a c. So, if it is around point if carbon content is around 0.4 this percentage pearlite will come out to be 0.4 over 0.8; that means 50 percent pearlite.

Similarly, you can calculate ferrite will be b c over a c, but bow it is also possible that you can find out the total amount of cementited total amount of cementited here, is just the cementited is present only in within the eutectoid structure. I leave it to you to find out what is the amount of percentage cementited here, also you will apply the lever rule and cementited composition is given by this point and you say that ferrite will ignore the solubility of carbon the ferrite composition is given by this point and this is the composition from the steel.

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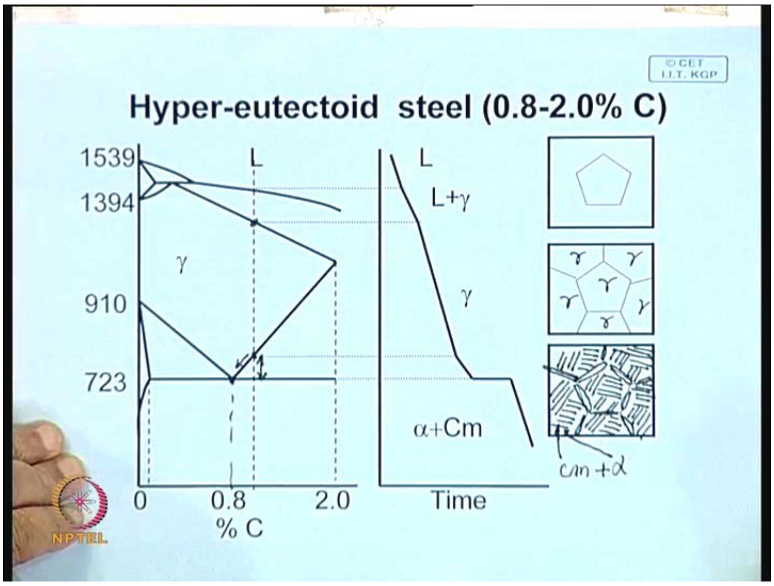

Now, how about the structure of hypo Eutectoid steel now here it will also follow I mean the process of transformation will be exactly to one that we consider in the case of Hypo-eutectoid steel. Now here, again the cementited will start precipitating out at the temperature say until here. It is normal solidification which we have seen in many most cases. So, in this temperature region here the solidification is complete you have austenite. So, these are the austenite grains and when cementited starts precipitating out always it is the grain boundary where the amount of cementited will form and cementited is the tendency it will form along the grain boundary.

So, it is the possible that you will get cementited forming in the grain boundary region this is the pro Eutectoid cementited. And all this process of cementited along the grain boundary in this temperature range and once this Eutectoid temperature is reached because, as this temperature goes down the composition of austenite changes long this then austenite becomes less rich in carbon and ultimately when it reaches 0.8 percent cementited and ferrite start precipitating and you have pearlite formation in this zone.

So, you will have this kind of structure you will have a network you will have a paralytic region pearlite is not a phase it is a mixture intimate mixture of two phases that is commentate. And ferrite these are intimate mixture of two phases, so line I am representing this line represents cementited this white region represents ferrite white portion represents ferrite.

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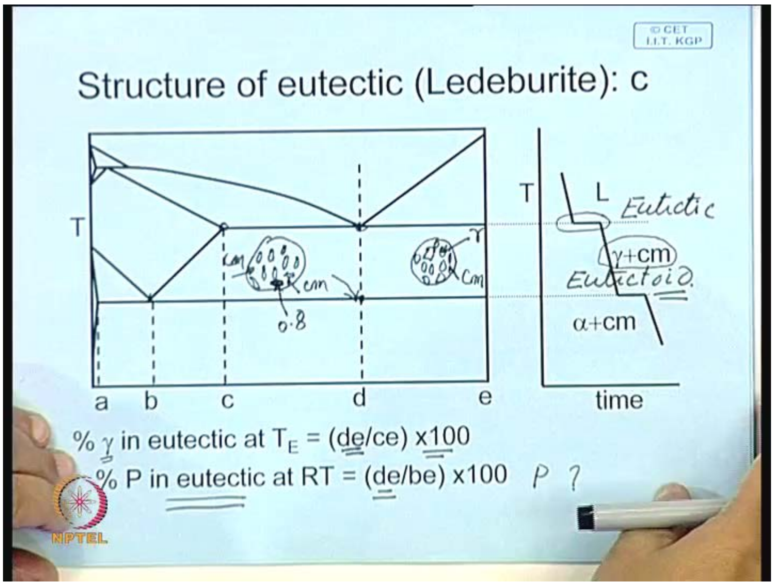

And here, also I will leave it to you to calculate the amount of the different phases in hyper eutectoid steel. So, now, let us look at the structure of that was solidification of the eutectic means over here, now the cooling curve will look like this you will have one isotherm now here this is the Eutectic and another isotherm here; so, this is Eutectoid.

So, here you have here you will have austenite and as the temperature goes down from the here you will have the intimate mixture of austenite cementited that is the Eutectic structure, and Eutectic will be a mixture of let us say that a mixture of austenite and surrounded by so these are austenitic region and. So, you will have intimate mixture of austenite and cementited and this from this austenite as the temperature goes down, because the solubility of carbon in austenite goes down amount of cementited will come out. So, when it reaches this temperature you will have even more amount of say amount of this austenite region they will shrink and more amount of carbon will precipitate as cementited; so, this area is cementited.

So, here whatever amount of austenite you had take which is shown over here at this Eutectic temperature you can calculate the amount of Eutectic product this amount of austenite in Eutectic this is e d over c e and amount of that when you cool further what happen here, you have austenite composition is change initially you have 2 percent carbon. Now this austenite carbon is 0.8 percent carbon and this is cementited now this austenite gets converted into pearlite. Now pearlite you can find out how much is the amount of paralytic region in the Eutectic and this will be given by pearlite amount will be d e over this entire amount is b e.

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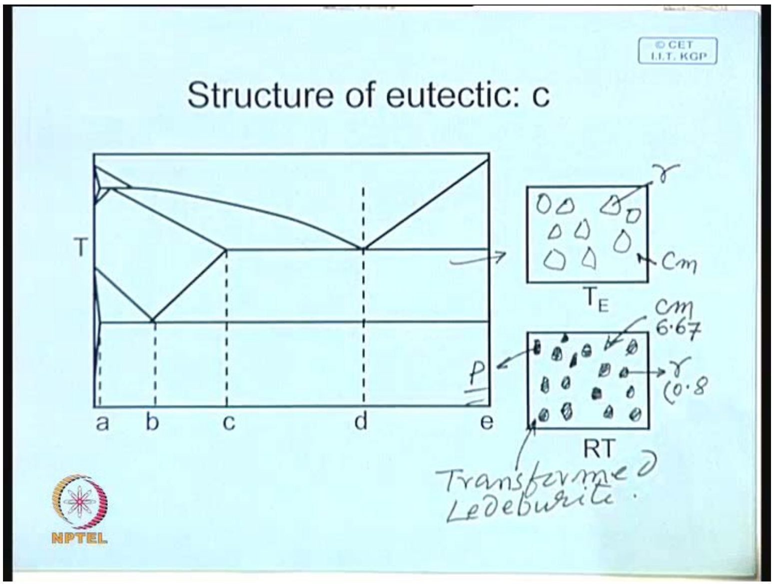

So, here I think just explained so here you have the Eutectic temperature so here your structure will be the best will be your austenitic region; so these are your austenite this is cementited, and as the temperature goes down from this austenite cementited precipitates out.

So, they becomes smaller and at Eutectic temperature this is cementited which has a definite carbon content 6.67 and you have some of these austenite with carbon content

0.8 percent. Now as you cool down further this austenite gets converted into pearlite so you have this lamellar structure and it will be more and this percentage is can be estimated using lever rule. So, this is called transformed Ledeborite so what you will have really you will have some areas within this microstructure which will appear like intimate structure pearlite region. And which will be surrounded by cementited. So, this is each of these which were earlier austenite it will be pearlite.

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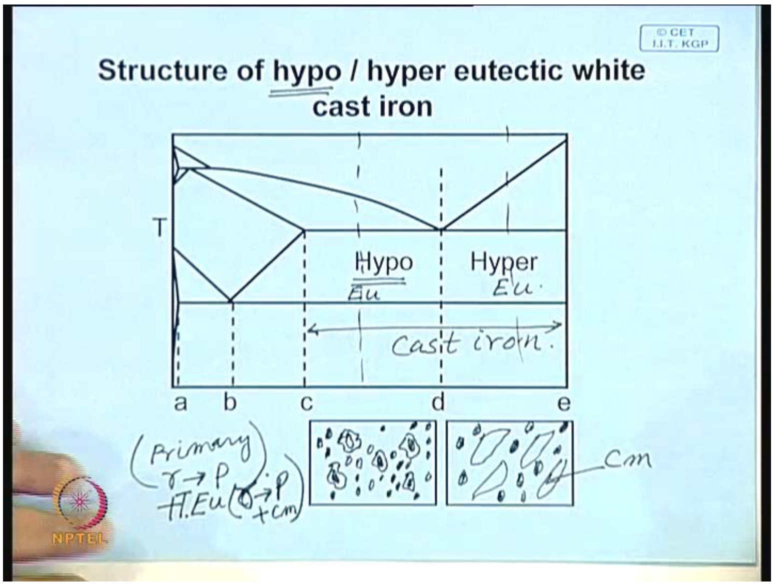

Now, in the same terminology we can use to represent this alloy that these are called hypo eutectic alloy. Hypo- eutectic this side is hyper eutectic and this as I said and this area cast iron and what will be the structure of a Hypo- eutectoid cast iron. Here when it solidifies primary grains of depending on the composition where you are and when Eutectic isotherm is cross you cool below the Eutectic isotherm. Here, you will have that Lediborite structure form; so Lediborite structure will form and as you cool further; this austenite will shrink and some cementited will precipitate out, they will shrink these also will shrink and when this temperature is crossed.

You will have, all these will get untransformed austenite will get converted into pearlite. And the structure will look of as you have primary austenite which is converted into pearlite you will have Eutectic that is transformed Eutectic which will consist of basically, transform austenite which is transformed into pearliest plus cemented. So, morphology little different here also it will be exactly similar same way you can draw the microstructure these are cementited and this area will be the transformed Eutectic.

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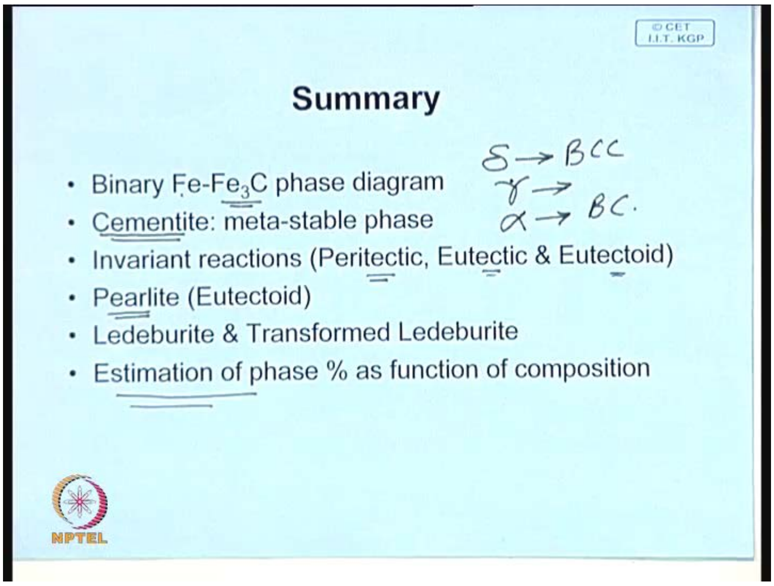

So that means look at know the phase diagram possible to find out; will be its micro structure and this micro structure will be and, enthuses again and again those properties of a material the function of the micro structure; microstructure you will be able to guess the properties next class we will see some examples. So, today what we did. So far, is we looked at binary iron carbon phase diagram basically iron cementited phase diagram the cementited.

We talked about a cementited which is a meta stable phase, we also talked about the crystal structures of iron and how they are known as, so that is called delta which is BCC then austenite. And then we have low temperature BCC structure talked about three invariant reaction paratactic Eutectic; Eutectoid we talked about paralytic structure, which is a Eutectoid structure. We talked about eutectic Ledeburite transformed Ledeburite, and we also saw some examples, and how to estimate percentage phases as a function of composition. Thank you.