Phase Diagrams in Material Science Engineering
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Lecture – 36
Cast Iron- I

Students, we have discussed a lot about steels and their micro structures in the last two weeks. So, I am going to start on cast iron this week, and we are also going to spend about 4-5 lectures, on different discussions regarding cast iron, but before I do that let me just remind you that in the last class, I have discussed with you a very important concept, and that is a TTT diagrams for steels.

TTT diagrams are very important, not only for the scientist, but also for the people, for this engineers working on the shop floor. and these diagrams are important for different heat treatment processes of steels. So, it is required that you understand; how to read this diagram and interpret. So, I will just spend about 5 to 7 minutes on these diagrams then I will move on to the cast irons. So, this is a typical, you know TTT diagram of 1 0 8 0 eutectoid steels; that means, this is a plain carbon steel consisting of about 0.8 percent carbon.

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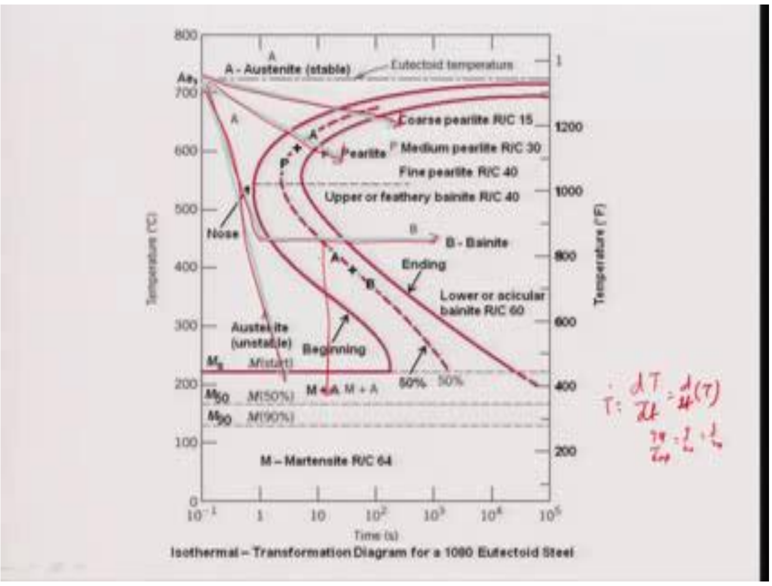

Isothermal – Transformation Diagram for a 1080 Eutectoid Steel

Now, if you look at this diagram there are two axes; temperature on the vertical, time on the horizontal axis, and as you see that on the right side of the vertical axis we have also plotted temperature in Fahrenheit, on the left side we have plotted temperature in degree Celsius. And inside whatever is there, they are in different colors. First of all, the things which is looking like a sea capade is what is more important, and as you look at it, this is the a one temperature maintains a e 1 temperature, a 1 temperature is the eutectoid transformation temperature, above which austenite is stable, below the temperature austenite is not stable. We have seen austenite can undergo three different types of transformations; austenite to pearlite, austenite to bainite and austenite to martensites. And you can also mixtures of pearlite plus bainite plus martensites and martensite plus austenite as retained austenite is possible.

So, what you see here is this a curve; this one the left side of this curve, it is shows you the beginning of the pearlitic transformations, a beginning of rather you can say transformations which are pearlite or bainite, and the right side one is basically called end. So, beginning means 1 percent transformed, 1 percent of austenite got transformed. It can be pearlite or bainite and end means 99 percent austenite has got transformed, and in between we have also a curve 50 percent transformed.

And then that is the one part of the diagram, next part of thing is, you have a martensite start temperature, martensite 50 percent transformation temperature martensite 90 percent transformation temperature, they are well below the you know the pearlitic or bainitic transformation temperatures. So, this is what is the actual diagram looks like. I am not going to do, go back and tell you how this diagram has been obtained that I have done lot in the last few lectures. I am just only going to tell you that how to read it. these are the diagram important curves which you need to know.

Now, this is a plot between temperature versus time, we can actually plot different cooling rates cooling rate is nothing, but the d t; d T by d t, this is what is cooling rate. So, that that is nothing, but d d t temperature. So, that is the slope of this curve, as you see here, I have drawn four different lines each one signifying a cooling rate. So, let us first start with a slowest cooling rate. So, that is this line I am drawing it again. If I cool it so slowly very slowly, I am cooling actually it about 100 degrees from suppose 723 to 623 or 615 Celsius in about say, couple of degree times on second times say about 600 times 600 means 10 minutes time very slow cooling rate. So; that means, one it is about 90 divide by 600; that means, it is basically, very low 90 divide by 600is how much; is 9 by 60 is 3 by 20; that is a very slow cooling rate correct even less than 1 degree per second. So, or if you consider minutes it is basically, about 9 minute 9 degrees per minutes ;that is not fast that is very slow.

If you cool it that slow what you will do if you cool it this slow that cooling curve will cut, the start or beginning pearlitic transformations, and because of these you are going to we are going to have pearlitic transformations started, and the pearlitic transformation will keep on going on and it will lead to formation of coarse pearlite that is here coarse pearlite will be very high for the pearlite, and the hardness will be r c 15. If you cool it a little faster, let us suppose if you cool about say 20 degrees per minute then you will pearlite, because it will pass through these pearlite transformation curve, but it will be find pearlite hardness will be almost double r c 30 r c 40.

Now, if you cool it this is a finally, that is a second third curve, if you cool it fast initially to bypass the nose of the beginning curve and keep it there for longtime, then you will have bainitic transformations and this bainitic transformation lead to formation of bainites in the form of upper bainites, because, it is at the upper temperature 9 4 50 degree Celsius temperature.

On the other hand so; that means what if I cool quite fast initially to bypass the pearlitic transformation and then keep it for longtime. I am going to start the bainitic transformations. And the last one is basically, this one you see here, the very fast cooling, if you cool it very fast is you are cooling 700 to 200 Celsius 500 degree Celsius temperature in about say 5 milli seconds so; that means, 40 degree per second; that is a very fast cooling; that means, 40 degree per then 24 240 60 2400 degree Celsius temperature per minute. So, in a couple in a few seconds you are getting the sample temperature going down to room temperature from 700 that is a very fast cooling. If you do that you bypass the nose bypass the barnite transformation what you land up is lands up in basically, in the martenitic transformations region that is same as start and you form martensites, that depending on how much you cool how fast you cool martensite transformation will stop at 50 percent or 90 percent.

So, these are the way these curves to be; that means, if you want to generate a particular micro structure, for a particular composition of steel you get this d d t curves in the steel from different sources and then draw this cooling curves, and then you will understand whether you have to go for you know air cooling or water quenching, wall quenching or wall quench, water quenching, and then followed by isothermal holding at bainitic transformation. That is what is your requirement you can produce mixture, you can form certain fraction of bainites and quench it will form martensite austenite. Suppose, if you cool a like this hold up to this point temperature and quench, what will happen you will have barnite plus martensite mixture. So, as you see here the cooling rate is very high for martenic transformations.

That means, what you have to quench very fast, and if you quench the sample you will form thermal stress and thermal stress will lead to formation of cracks sample will break. So, therefore, to you need to avoid that we want to reduce the cooling rate, or we want to you know make the cooling slow, so to do that you have to add alloying elements.

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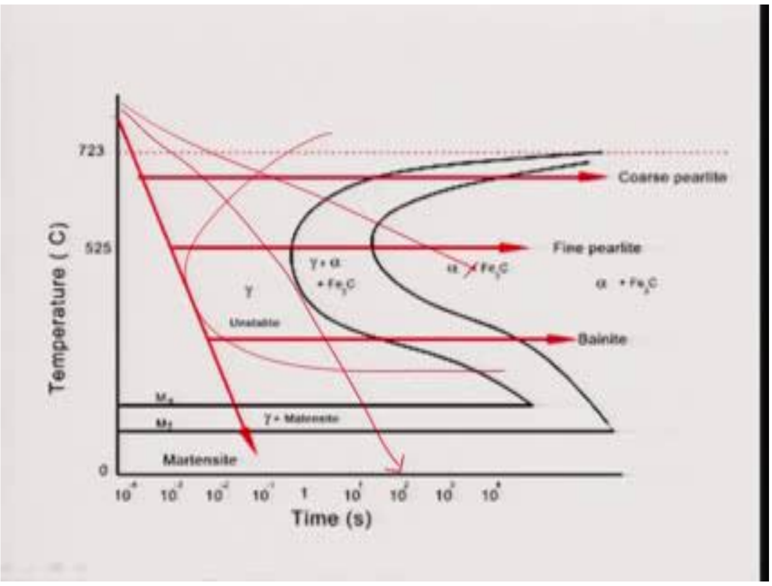

So, if I you are alloying elements what the alloying elements do is basically, they shift is right side. So, earlier this was the cooling rate, you see earlier curve was like this. These are the critical cooling rate for martensite transformation. Now, this has become the critical cooling rate. So, you can see which one is slower very easily. So, that is the why we add manganese, why we add chromium, we add tungsten, we add many other stuff to reduce this cooling rate from martensite transformations; that leads to not only that it will also just slow down the pearlite transformation cooling rate, you see here this is what the pearlitic transformation cooling rate that is also very slow.

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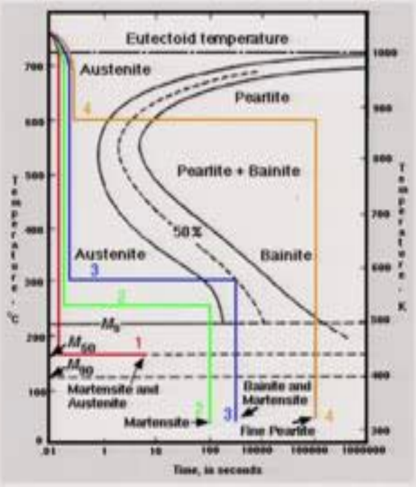
Typical T-T-T Diagram for 0.2%C Steel



So, this is exactly whatever I told you I am showing here for 0. 2 percent carbons let us 0.8. So, only thing it will change is that these shapes will remain same only thing it will change is the position of these curves. The carbon is also alloying elements, but not like other alloying elements carbon is, you know steel metallurgy, we do not consider carbon to be alloying element as a part of alloying element like you know moly, like tungsten, like manganese, carbon, is different we consider.

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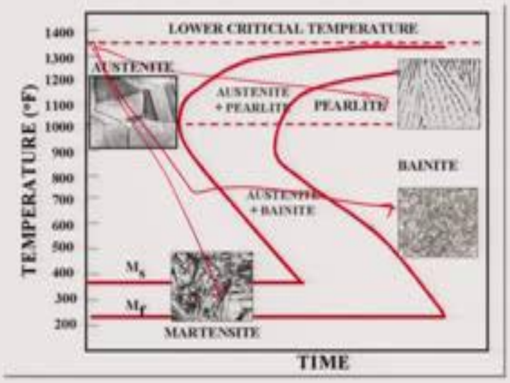

Now, this is what is with the microstructure. Many times you will find as the kind of diagrams, temperature is Fahrenheit versus time, you see here this is austenite, metastable, austenite you can have pearlite you can have bainite, you can have martensite at different tones. So, if I cool it down like this I will form martensite, if I cool it down like this I will form pearlite, if I cool it like this and hold it will for bainite. Thus the way sees you can represent this diagram in many ways fine.

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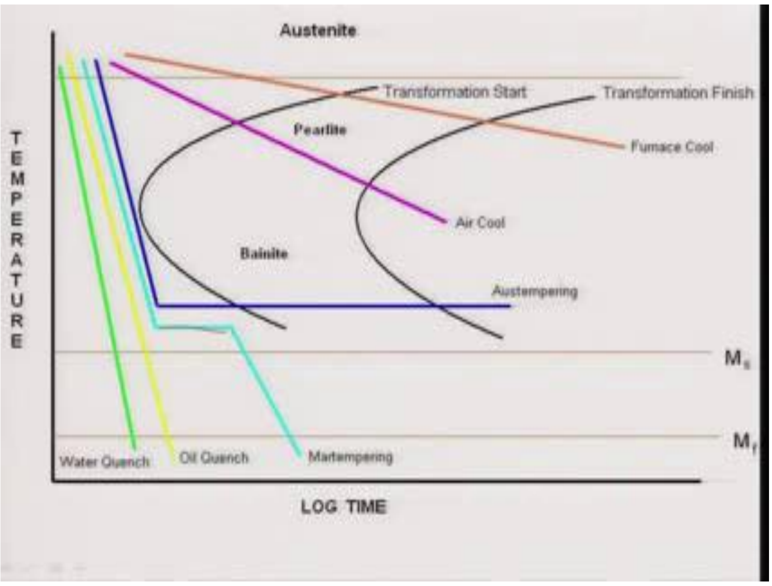

So, you know another way of doing this is, yes there are few more things I will say there are different kinds of cooling's; one is the cooling other one is the way of cooling it is a furnace cool, this is what is the slowest cooling there possibly form coarse pearlite. If we add cool take the sample out from the furnace and keep it in air will form this is the cooling rate will form fine pearlite. If you cool it like this and isothermal hold for long time is what is known as austempering.

Austempering is what? You transform the austenite to bainite that is called austempering. So, to do that you cool it quench it like this, isothermally hold it at about 200 degree Celsius temperature. Now, if you cool it water quench you bypass the nose of this curve pearlitic transformation curve you form martensites, but cooling is very fast in water quench, because slow it down by oil quench depending on how is the nose situated the nose is, very close to the vertical axis then you have to go for water quenching if it is not. So, you can go for oil quenching this is another transformation very interesting what is known as martempering. You cool it keeps it there. So, that you form martensites. So, know.

So, that you have formed little bit of bainite, and then you quench it. If you quench it based austenite you form martensites. So, these one will lead to lower bainite plus martensite. So, you can see you have varieties of cooling paths possible, and you can impose. You can actually ingeniously generate different kind of cooling situations or cooling rate situations, and create different type of microstructures that is the beauty of steel metallurgy.

In steel it the properties of the steel can be monitored many ways; that is what is not understood by the physicist or the chemists compared to metallurgists, very lighter side this is what I can say, because we can take the same composition of steel, and we can change the parameters we can generate different microstructure, and by different microstructures we can have different properties, and that is what is our end game right you have to have properties of the material which is useful. So, to obtain that basically that things we simply can have different cooling rates; different cooling rates means different environment, different environment means different ways of you know changing the microstructure; that is what is done in the heat treatment of steel. I do not want to go into this. This is what is this effect of alloying. So, that is not required.

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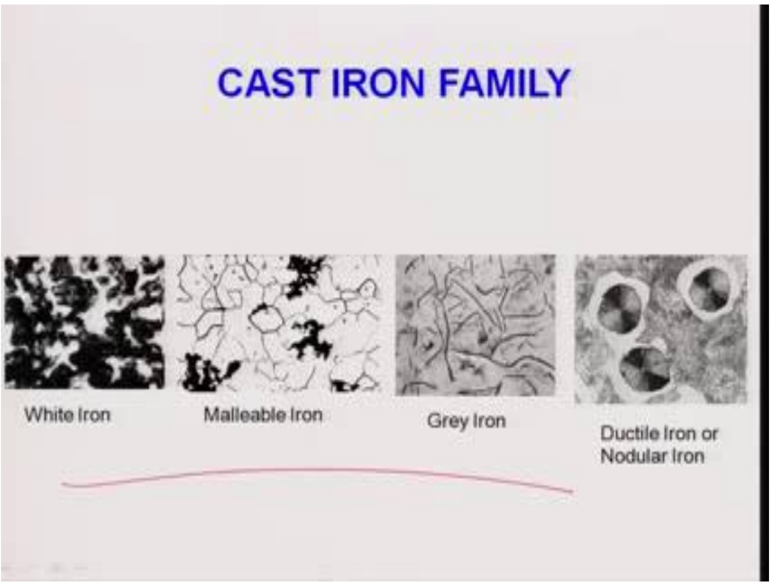

CAST IRON FAMILY

Now, so far I gave you a again (Refer Time: 13:23) of knowledge or basic understanding of this cc two curves now let us move it to the cast iron family, you know cast iron like steel is also very important material. In fact, if you go to automobile industry cast iron has cast iron, has a lion share in the automobile industry, not the steel, cast iron is widely used in automobile industry cars, trucks, and many other you know things a trolley, this is what is the material used to make different components, and I do not want to give this basically has a very large share. So, therefore, it is important that we understand, but you know difference between steel and cast iron is that, steels have very low carbon; that is the first thing. Steel contains about maximum 1 percent carbon, and majority of the steel contains about 0.2 to 0.5 percent carbon on the other hand cast iron carbon concentration is much larger. It can be 2.5 to 4.5 percentage that is the first difference.

They are iron carbon alloys, but they are not same as steels cast irons are. Second important issue is that we have lot of silicon, in cast iron which is not there in steels except spring steels which while, we are interestingly add silicon to increase the elastic strength. Almost all the steels will not have mass silicon on the other hand cast iron invariably have 1 percent or more than 1 percent silicon is required. I will explain you why it is required. So, as you know cast iron also has varieties like steels. So, you can generate different micro chain in cast iron that is the beauty of it and that is why they are very interesting and you need to understand; like here white iron malleable iron grey iron ductile and nodular iron four different types of cast iron. I am showing in the pictures. You see here these are the four different there are many more that is there actually; like permisular cast iron or alloy cast iron, which we will discuss maybe in the after sometime, but not today.

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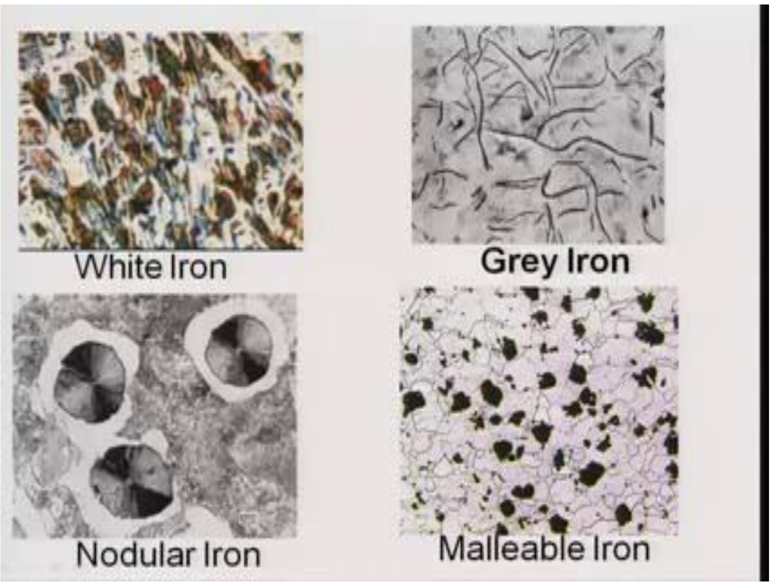

Now, let us discuss what is this. So, this is again in a snapshot; this is white iron, while we have no graphite, and then grey iron, while graphite is like a flex; nodular iron graphite or graphite is like a nodule, and malleable iron for graphite is like a same part or graphite is like irregular shapes correct. So, basically, what in grey iron, nodular iron and malleable iron, we change the graphite morphology, but in case of white iron what you have is basically, cementite not graphite at all.

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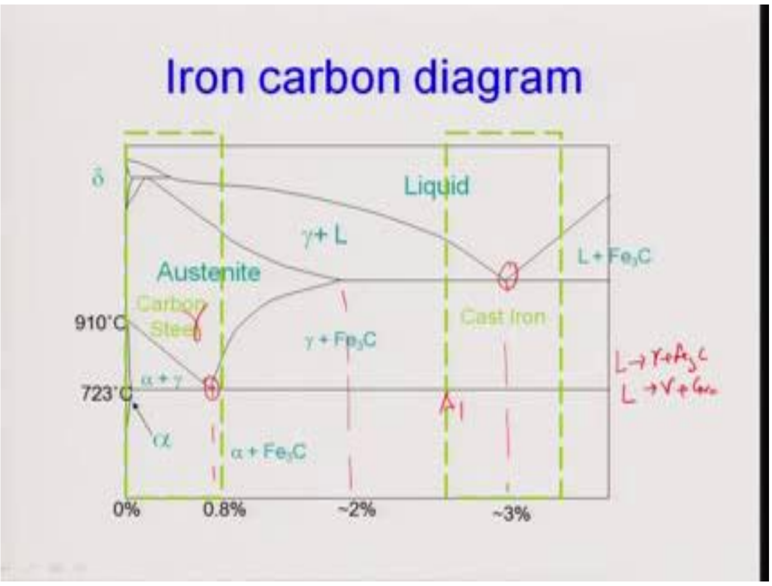
Iron carbon diagram

Let us now, discuss in terms of phase diagram, because this is a course on phase diagram. So, you have to understand that. So, as you see here this is the iron carbon phase diagram normally people tell, but this is not today we will come to know. So, as you see here you have pearlite a one temperature below which is the pearlite transformation happens; that is called alpha plus cementite. I discussed a lot about it, then you have austenite or gamma, then you have cementite on this side.

So, these are the carbon percentage it is in 0.8 about 2.01 percentage, it is about 3 percent carbon. So, this is what is it is. Now, you know this is the region on which steels were discussed. Only thing about steel, I did not discuss which I will do is this peritectic reaction. I told you for low carbon or stainless steels we have a chapter on stainless steel where this will going to come into picture, but I have discussed about whole thing.

Now, cast iron forms. So, therefore, this is the region of steel right using see here, I have marked by green box. Now, this is the region on which cast iron composition falls, let us say 2.5 to 4.5 percentage. So, the important reaction which happens in this region is eutectic reaction which is taking place here, from the phase diagram perspective. We have to understand that reaction. On the other hand for the steel important reaction was eutectoid transformation reaction; that is what we have done. We have seen how austenite transform in to pearlite martensite or marite, but here, the most important issue is the eutectic reaction, which is basically, can be liquid going to gamma plus cementite or liquid going to gamma plus graphite. These are the two reactions which are there.

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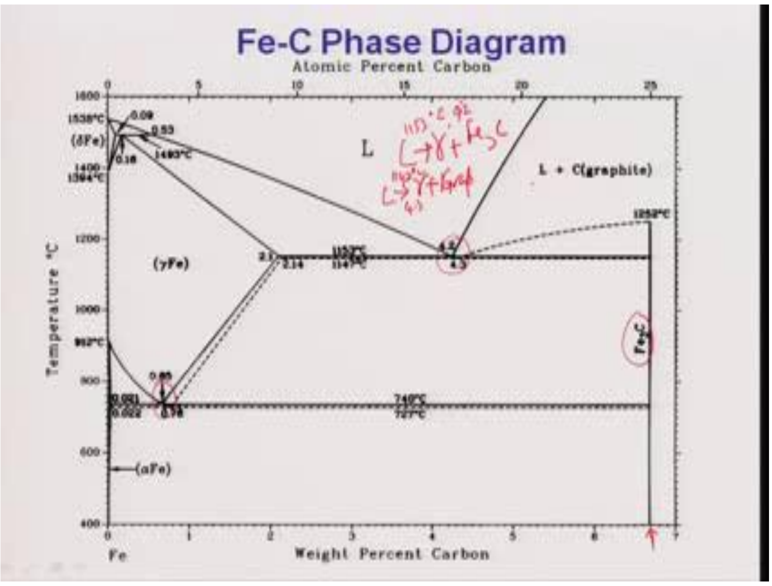

Fe-C Phase Diagram

Now, this is the diagram which I have got from professor Massalski's book called binary alloy phase diagrams. And here, you see there are two types of curves; one solid one other one is the dotted one. Now, we will I will make I spend about 5 minutes to explain you this is very important then we will go for the cast irons. As you see here the black ones or the solid lines that is basically, for iron carbite equilibrium; that is what is fe to c. See here iron carbide. So, therefore, those of you who were quite clever and intelligent they have already understood very nicely, and others will also understand after today's lecture, that steels are basically, alloys of iron and carbide. So, therefore, equilibrium which is important for steel is between iron and iron carbide. I do not know in iron carbide, the carbon concentration in fe 3 c is 6.67 percent carbon; that is why, I have told previously these diagrams ends at 6.67 percentage of carbon.

We do not discuss even what happens beyond this, and as a steels the carbon concentration do not go beyond one percentage in the actual practice, it can go actually theoretically after two weight percentage, but actual practice is we do not have steel level more than 1.2 weight percent carbon, as far as my knowledge goes. So, therefore, the important part of the phase diagram is that is what I showed in the last class is this part. So, the equilibrium which is important for iron steel is basically, between iron and iron carbide.

Now, equilibrium which is important for the cast iron, is not iron and carbide it is iron and carbon or iron and graphite. So, dotted lines are basically, equilibrium between iron and graphite. Solid lines are between iron and carbide. So, what are the difference you see here first of all you see, if you have a carbon or graphite, as a second elements or second you know entity component, then your these eutectoid transformation temperature and composition will change.

Normally eutectoid transformation temperature is 723 degree Celsius temperature and composition is about 0.8 percent carbon 0.78, 0.8, and if you had graphite then your carbon, these things shifts to 0.85. Similarly, this transformation thing is also gets modified this is about. Whatever, I discussed about these; what is the modification temperature; you take temperature whatever reaction I told you know liquid to gamma plus cementite is between iron carbide, this reaction happens at 1100 and 53 degree Celsius temperature with a carbon concentration of about 4.2 percent carbon.

On the other hand this take to reaction which is basically nothing, but when the equilibrium is between iron and graphite; that is what gamma plus graphite, and this reaction happens at 1147 degree Celsius temperature, carbon concentration is 4.3. So, as you see here, both the transformation temperature and composition changes if we had graphite as second component then carbide. This is what I want you to.

Now, understand very clearly this can be explained easily from the free energy (Refer Time: 21:50) which time permits, I will also do it; basically, equilibrium means what; heterogeneous equilibrium means what; as we discussed at the beginning of this course, is basically, you have to draw a common tangent between two curves; one is for the gamma, other one is for the cementite or graphite. So, wherever these common tangents will lie, that is what is the composition given, for the stability right. So, as you see here if for graphite, the maximum carbon concentration which can get into gamma iron is 2.14 not 2.1, 2.1 is basically, for iron and carbide phase diagram. So, everything gets modified. So, that is the most important thing you have to understand, and when you form graphite directly from the liquid. Basically, graphite has the different crystal structure; it has hexagonal crystal structure as you know.

On the other hand, cementite has an orthorhombic crystal structure. So, because of change of crystal structure solubility changes everything changes, basically for all our discussion which we did not bother about these things when we discussed about steel because steel graphite does not form at all. Cementite looks like it is a metastable phase, but it remains it can remain 1000 of years without transforming into graphite. Basically, cementite should not be present in steel, cementite is phase, if you heat it if you do something it will transform into iron plus graphite, but it does not happen in steels that is a god’s grace; that is why steel is better mean prior. Now in graphite that is still a different thing in graphite you have a transformation of this cementite to graphite that is what happens. So, you can either form cementite.

Now, in this regard I should tell you that that is why silicon addition is very important, why; because silicon actually allows the formation of graphite easily from the liquid in presence of silicon graphite forms more easily than cementite; why it is so? So, well that is mainly because silicon reduces the nucleation area of graphite; if you want to form graphite on the liquid you need to nuclear graphite and graphite has a structure it is a complex things and also it has a layer structure it is very difficult to (Refer Time: 24:13).

Silicon actually helps in formation of graphite nucleation there are many reasons for it how it happens this is still debatable, but still, but anyway that is what you should remember silicon helps in nucleating graphite from a liquid; that is why silicon addition is important and need a little bit of in a critical amount of silicon that is about 1 to 1.2 percent 1.5 percent or maximum 2 percent silicon is required to do; that is why most of these cast iron has silicon.

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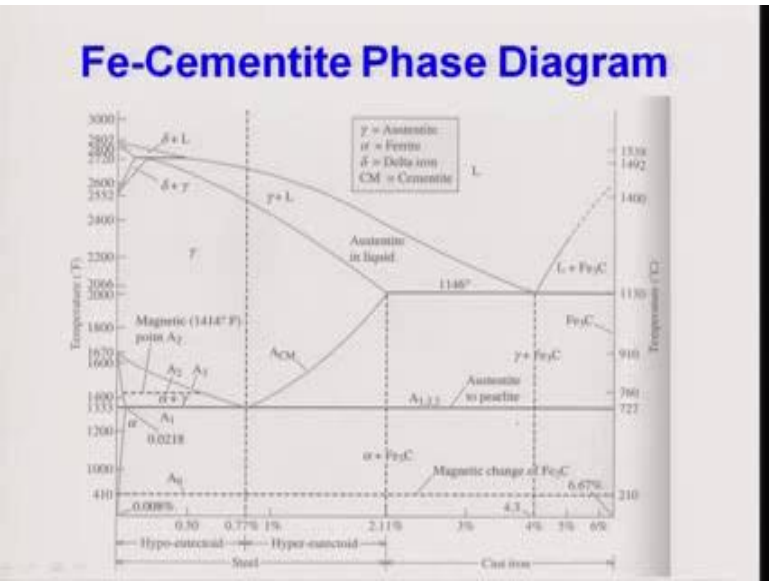

Fe-Cementite Phase Diagram

So, this is the iron carbide phase diagrams and before I stop this lecture, let me just explain where everything is given you, please read these diagram you see a 1 temperature a 2 temperature a 3 temperature a c m everything is written a 147 or 46 is the temperature a one temperature is what is basically, 723 to 27 degree Celsius temperature there is something also known as a 0 temperature which is I have never told and I should tell you a 0 is what because everything should start with a 0, a 1, a 2, a 3, a c m, a 0 is the magnetic change or fe 3 c, fe three c also becomes magnetic at 0.10 degree Celsius temperature that is what is the meaning of this. Other than that please, this diagram you must have you must be very comfortable with it that is very important diagram for most of the materials, we use in our day to day life that is steel and cast iron.

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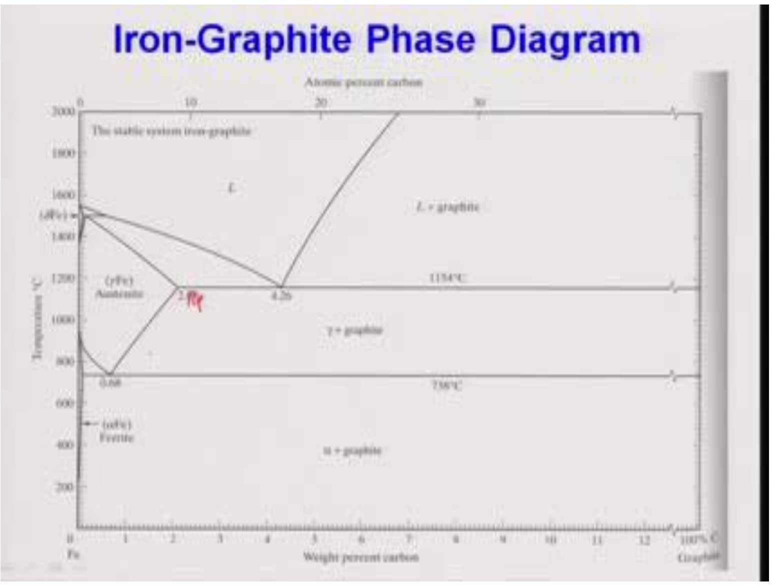

Iron-Graphite Phase Diagram

On the other hand this is the graphite phase diagram, you see here this is 2.14 this should be 2.14, 6.8 to 4.26 eutectoid transformation temperature is about 700 and 36, and this temperature is 1,154 degrees Celsius temperature.

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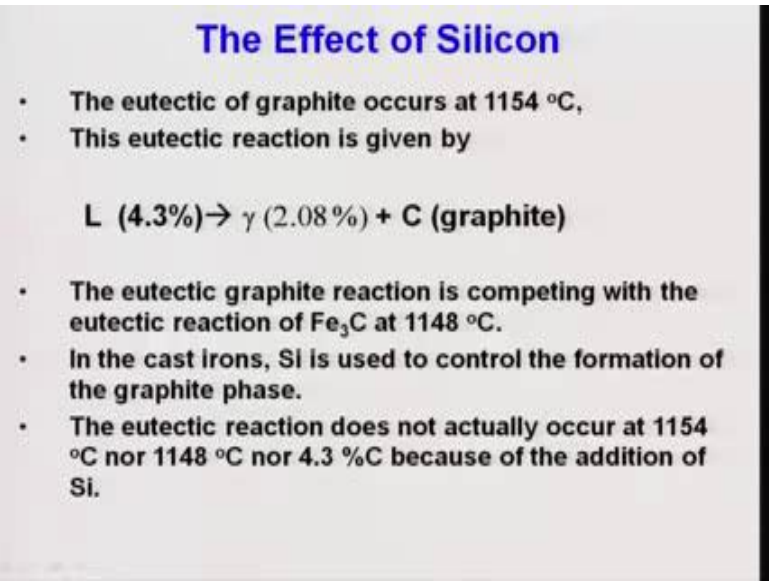

The Effect of Silicon

- The eutectic of graphite occurs at 1154 °C,
- This eutectic reaction is given by

$$L\ (4.3\%) \rightarrow \gamma\ (2.08\%) + C\ (\text{graphite})$$

- The eutectic graphite reaction is competing with the eutectic reaction of Fe_3C at 1148 °C.
- In the cast irons, Si is used to control the formation of the graphite phase.
- The eutectic reaction does not actually occur at 1154 °C nor 1148 °C nor 4.3 %C because of the addition of Si.

In the next class we will start with the effect of silicon, and I have already given you the idea about the phase diagram. So, let us do that.