Phase Diagrams in Material Science Engineering
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Lecture – 34
Bainite Transformation

Students, today, we are going to discuss about bainitic transformation in the steels. I have introduced it to you in the last class, and we are going to discuss in detail. As I told you that, in steels, austenite is the high temperature F C C solid solution of carbon and iron, and there are three different path ways of transforming austenite. One is the classical way of forming Pearlite from austenite, just by cooling below the A 1 temperature. Second one is the rapid quenching of steel from austenitic state to Martensite; and third one, the most classical one I would say, is quenching the steel from the austenitic state to an intermediate temperature of something like 300 to 400 degree Celsius temperature, and keeping there for long time, will lead to formation of Bainite.

As you know, Bainite, the name, came from the scientist called E C Bain, or Edgar Bain, who discovered the way, or mechanisms of martensitic transformations.

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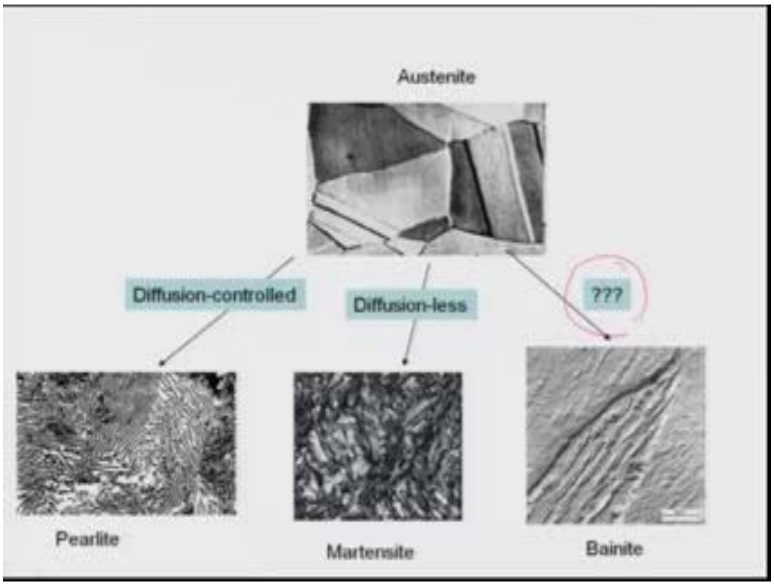

So, therefore, in all the slides, as you see here, Bainite transformation which forms from austenite, I have written the mechanism as a sign of interrogation. The reason is that, it is not yet fully understood, what actually happens. But, let me just tell you briefly, what actually happens. You know, bainitic transformations is, the product of bainitic transformation is again Ferrite and Cementite. But, their morphologies are different, which we will discuss again in the some slides; morphologies are different.

In Pearlite also, you have Ferrite and Cementite, but Pearlite forms the lamellar morphology, in which the growth is dominated by the carbon deficient, in the, from the Pearlite, the product phase to the parent phase, across the interface between these two.

And, it leads to formation of lamellar morphology, which can be easily explained, like I have done in the class a few lectures back. Martensite is diffusionless transformations, but, in this Bainite, you form the same component of, like Ferrite and Cementite as the microstructural species; but the formation is different. In fact, Bainite forms in the temperature range which is intermediate between Pearlite and the Martensite. You know, Pearlite transformations stops to happen at about 400 degree Celsius temperature; that, what does it mean that, Pearlite temperature starts at a 1 temperature, but it will, you know, as the temperature goes down, as the deficient of iron and carbon will be very, very slow at low temperatures, so, therefore, the transformation actually, almost stops at about 400 degree Celsius temperature.

So, as the temperature decreases, the carbon deficient is slower in the austenitic phase, the meta-stable austenitic phase, below a 1 temperature, and because of that, pearlitic transformations become very slow; the inter-lamellar spacing becomes very small; and, as a inter-lamellar spacings become small, the interfacial area between the, between the Ferrite and Cementite will be very large. And, system needs to provide that energy. You know, and therefore, it is very difficult to, you know, have the transformation at a low temperature, when driving force, fixed driving posts are available. So, at about 400 degree Celsius temperature, the Pearlite transformation competes, or Bainite transformation compete with the Pearlite transformation; all the products are same. So, this is the upper end of temperature at with the Bainite transformation can happen nicely. It will not, the Pearlite transformation will not interfere with the bainitic transformation.

On the other hand, at the lower temperature, you know, Martensites, Martensites forms below m s temperature, as I discussed with in the class. So, at lower temperature, normally, 100 degrees above the m s, is what is the lower temperature of bainitic transformations. So, it is some sort, like 400 to 250 degree Celsius temperature for most of the steels, in which the bainitic transformation happens.

Now, very funny to understand that, you know, as the temperature decreases, as you decrease the temperature, the diffusivity of both carbon and the iron will be decreased; that is very simple to understand. Diffusivity is to given by this equation D, stands for diffusivity, equal to D zero into exponential minus Q by RT. Why D zero raised to p exponential term, which is a constant term; Q is the activation energy and R is the universal gas constant, and, T is the temperature.

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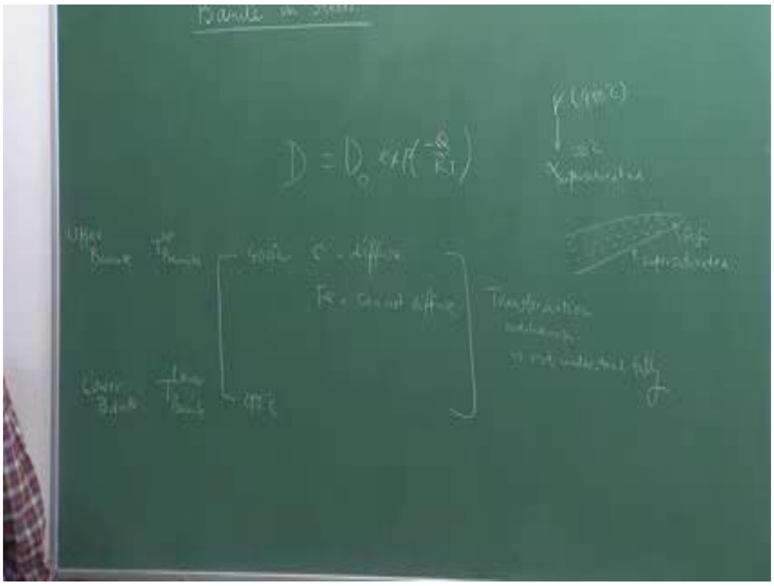

This equation clearly tells you that, the temperature decreases, diffusivity will decrease. So, at very low temperature, like 350, 400 degree Celsius temperature, or even, you know, diffusivity of carbon may be, may be a significant, but, iron will not move at all; because, iron diffusivity will be very low at 400 degree Celsius temperature; that is because, iron melting temperature is very high, about 1439 degree Celsius temperature, and iron is a, you know, iron atoms sits in the lattice positions unlike carbon atoms, which sits in the interstitial positions.

So, therefore, to move the iron atom, even for short range, change of the ordering, is very difficult, at about 400 degree Celsius temperature. So, in Bainite transformations, carbon atoms, diffusion of carbon atom do happen, from one interstitial position to another interstitial positions, but, iron atom do not diffuse at all. So, only way iron atoms can change its position, from austenite to the Ferrite plus Cementite mixture is by the movement as happens in case of Martensites.

In Martensites, normally, shear movements, shear forces moves iron atom from one atomic configuration to other atomic configurations, when the austenite transforms to B C T Martensites. But here, in this case, in austenite, same thing happens for iron atoms; iron atoms undergo these shear induced movement because of the transformations; but, carbon atoms can diffuse; carbon atoms can undergo, you know, classical diffusion because of this smaller size of the atom, and it moves from one interstitial position to other interstitial species. So, that is not a problem.

So, in to the classical Pearlite transformations, here, the diffusion of both iron and carbon atom are not happening in the same way; or, movement of the carbon atom and iron atom are not happening in the same way. Carbon atoms are able to diffuse, although a slower rate, but, iron atoms were not at all. When compared to Martensite transformation, where both carbon and iron atoms basically move, because of the application of the sheer force in a cooperative manner.

In Bainitic transformations, both the atoms are not undergoing changes from position, due to this shear force, but, only iron atom is undergoing. That is why, Bainitic transformation is very, very complex. And, it is, it cannot be explained only like diffusionless transformations, or a shear induced transformation like Martensites. So, that is why, I always put a, you know, sign of interrogation in the, in the bainitic transformations. There are lot of, you know, theories available to make it a diffusion transformations partially, or a partially you know, shear induced diffusionless transformations, but, none of these are 100 percent correct. It can be true for particular steel, or a particular composition of steel, but it is in general it is not happening.

So, that is why, bainitic transformation is little bit complex. So, at about 400 degree Celsius temperature, carbon can diffuse significantly, diffuse, but iron cannot diffuse at all. And, 400 is the upper temperature for bainitic transformations. This is the, you know, T u up for baininitic transformation. And, on the other hand, 250 is basically, sorry, 250 is basically the lower bound of bainitic transformations. So, T lower, Bainite, normally. So, as you can see, at lower temperatures, iron cannot diffuse at all, or even, even short range orders transformations; short range order means small change of this structural order is not possible, you know, iron cannot do that also. So, only way we can move the atoms from austenite to the mixture of Ferrite and Cementite, is by the military movement, this by that, you know, application of forces.

On the other hand, carbon can diffuse, although, at a higher temperature, you can diffuse significantly; at lower temperature, it cannot diffuse. So, that is why, this whole transformation mechanism for bainitic transformation is still, transformation mechanism is still not understood fully; not understood fully. I can make this statement, and how this transformation actually happens. So, that is the important thing you have, you have to look at it. As I told you that, there are two types of Bainites. The Bainites which forms at a higher temperature is called upper Bainite. The Bainite which forms at a lower temperature is called lower Bainite. So, this is what is called as lower Bainite, and this is what is known as upper Bainite. That is what I wrote, up and low.

So, what is the structural difference between these two? In case of upper Bainite, it is a plate like morphology, and in case of lower Bainite, it is basically a sheath like morphology. Let us first discuss a lower Bainite. What actually happens, when the transformations happens at lower temperatures, that you know, austenite gamma, it transformed to alpha, super-saturated. So, as you cool down, so, austenite is 950 degree Celsius temperature; see, if you cool down this to about 250 degree Celsius, austenite, which can accommodate a lot of carbon, will transform into super saturated alpha; and, this alpha will come like a plates, or like, as well as sheath like morphology, I would say. And, these are super saturated alpha; super saturated alpha; super saturated in terms of carbon. Obviously, alpha cannot take that much of carbon; you know, B C C iron cannot take more than, you know, 0.02 percent of carbon, at about a 1 temperatures. So, this, whatever carbon will be remained is super-saturated

Now, at lower temperatures, this carbon then precipitates as a Ferrite. This carbon precipitate as Cementite, sorry; these are all Cementite. That is what happens, and it is easy to understand. This is what happens for lower Bainite. Now, upper Bainite, this case is little bit different. As I told you in the class that, upper Bainite will be having gamma, 950 Celsius temperature.

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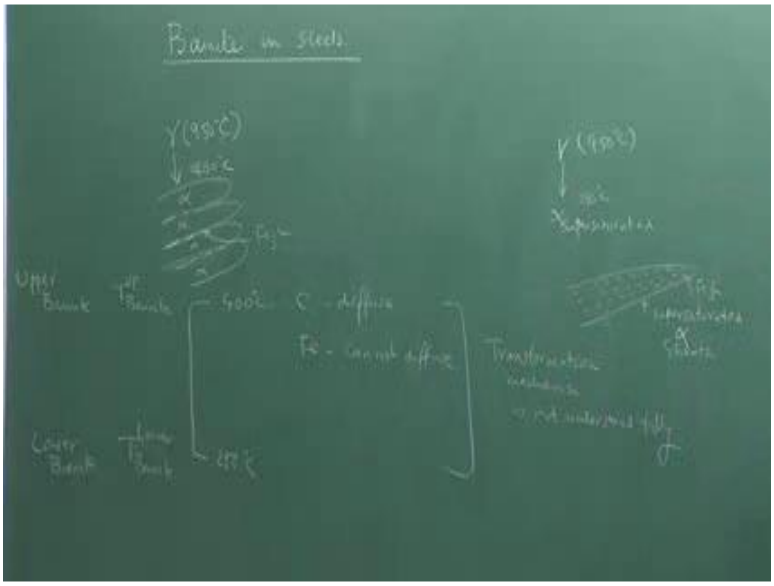

And, this will transform into this alpha. This is alpha; let me write down; super saturated alpha, obviously. So, alpha, and alpha will, lot of super saturated alpha will form plates like; and then, in between this alpha, plates, the Cementites, or let us put it this way. So, these are actually Cementite plates. So, these are actually Fe 3C; will precipitate, in between the plates; sorry, in between means, between the space between the two alpha plates. Here, what happens the Cementite is precipitated within the super-saturated alpha sheath; this is the sheath, super-saturated alpha sheath; you can call, it is just like a leaf, tree leaf. But here, the case is different; here, you have Cementite forming in between the two alpha plates; this is the alpha plates. So, that is the difference, actually. This is, if you cool it down to about, this is, this is lower; this is upper; this is cooling down to 450, 400 degree Celsius temperature that is what will happen.

So, this is the two morphologies normally observed in the bainitic transformations. Now, you know, if I play with the chemistry of the alloy, chemistry of the steel, and also play with the posing condition, I can make this plates nanometer thick, instead of micrometer thick, and make them nanometer thick. So, as you can make this a nanometer thick, the strength will be very high; ductility will also be very high. That is what Professor Harry Bhadesiya from Cambridge has done, and back he has researched so much so that, bainite is now, is a industrial product. Bainites actually is produced by Pasco steel plants in Korea as a industrial products, and these have some much higher strength than this classical Pearlite. Very fine scale Pearlite cannot match even the strength of Bainites. So, depending on your use, one can actually change these morphologies. So, you know, that is what the picture shows you; this picture is showing that, this is a alpha sheath in which the Cementite is precipitated.

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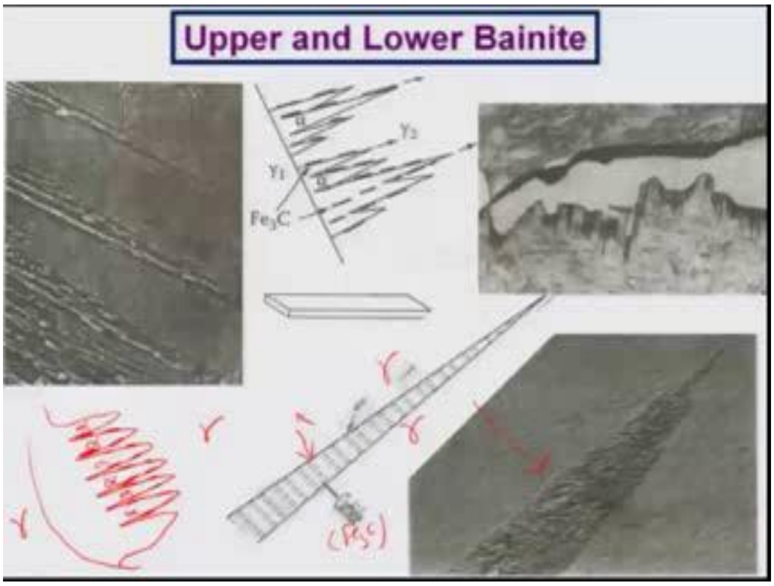

So, and, I have discussed with you about this, and, this is the picture I showed you just few minutes back. You see here, this is a leaf. This is basically a sheath, and in which Cementite is precipitated; and on both side you have, you have austenite. This is also austenite; this is also austenite. And, this is alpha; and inside of the carbides, mostly they are Cementite; that is what you see here in this picture.

On the other hand, you know, here, you see here, these are the alpha plates, which is happened for upper Bainites. This is the lower. You see here, alpha plates, and in between the alpha plates, this has Woodmans certain plates, obvious. As I discussed with you class, what happens when gamma transformed to alpha? It can happen this way; it can, gamma transformed to alpha, it can happen, this type of plates. These are called woodman certain plates. As you see here, so, this is suppose gamma, this is also gamma; these are the woodmans certain alpha plates. So, this woodmans certain alpha plates, in between the alpha plates, the Cementite can precipitate. This is what is shown in this picture. It is a Cementite precipitate. Basically, idea is to take out the extra carbon out of alpha. So, you can either do it by precipitating inside the alpha leaves, or you can do it in between; that is your, that is the choice of the system. And, depending on that, you create two different type of microstructures.

You may be thinking, which one will have better properties; obviously, the one in which the Cementite precipitate in between, will have, will not have good properties. Why, because Cementite is a brittle phase. And, as you know, if the brittle phase is remains within the plates, with a between the plates, then what will happen. This will lead to crack formations, and it will create problems of brittleness. On the other hand, the Cementite precipitates within this sheaths; this is the precipitaion hardened level system in which the strength will be very high; ductility will also be very high. That is the idea, and that is what, I have taken this picture, as I told you from Professor Bhadesiya's home page.

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You can look at it. It gives you very big descriptions of bainitic transformations, and how Bainites form. It is very nicely described. And, this is what is the actual thing I showed you.

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These are the, this is the alpha sheath, in which Cementite is precipitate out inside it.

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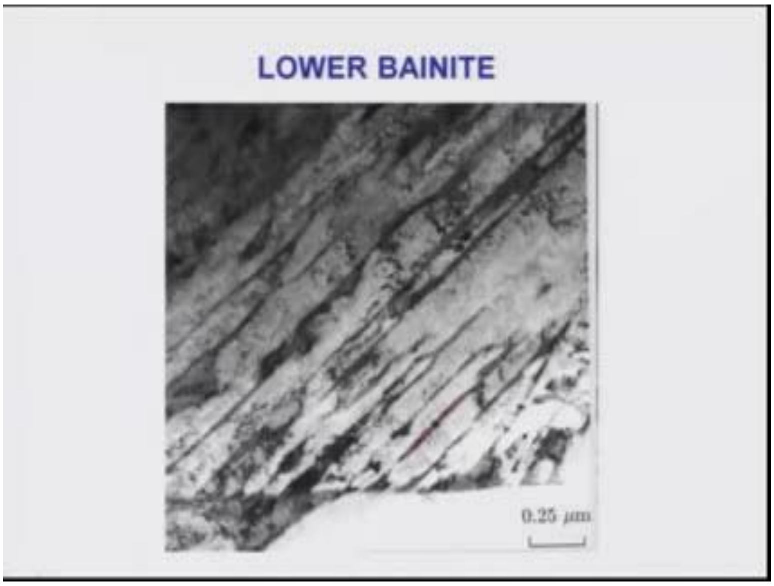

And, this is the lower Bainites, which is, sorry, this is not lower Bainites. This is higher, upper Bainites; you can see the Cementite has precipitated in between the plates.

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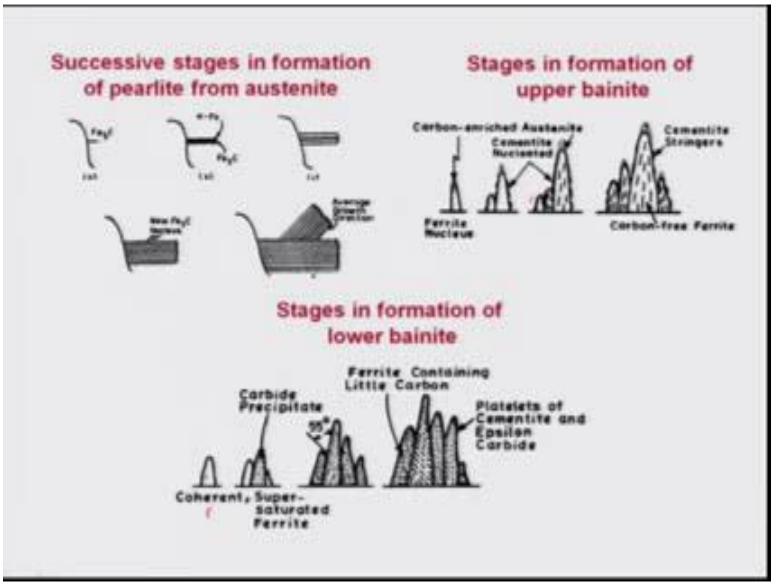

Well, so, I already discussed with you, stages of formation of upper Bainite, and lower Bainite. Let me again read it here. There is nothing wrong in telling you the things again and again. For the lower Bainites, as I told you, initially, this is gamma. So, alpha form coherently as a plates, or as a sheath rather; it is not a plate, sheath. And, it is a super-saturated alpha, as I board. And, in between the super-saturated alpha, the Cementite precipitates. You can see different Cementite precipitates. So, finally, you have a colony of this alpha sheaths. Inside each of these alpha sheaths, you have Cementite precipitate out; very nicely observed in the microstructures also.

On the other hand, in the case of upper Bainite, what normally happens is very simple like this. You have a Ferrite nuclei forms, and Ferrite glows rejecting little bit of carbon. When a Ferrite goes inside a austenite, it rejects carbon, right; Ferrite is very lean of carbon, and these carbides, these carbon then form, react with the iron, and forms the carbides. Here, you can see these are the carbides; correct. These are lot of carbides forms.

And then, actually, these carbides can actually form this, in between the plates. This is very, you know, this is happened when you possible, but this normally does not happen. So, that is how actually the both the phases, upper and lower Bainite forms.

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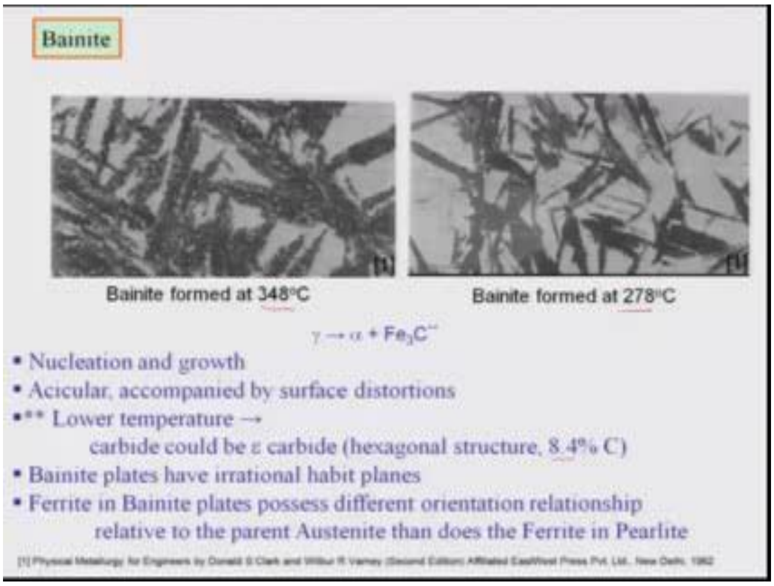

You know, that is what is shown here. You see here, the picture. This is taken from the book; you see, this is the Bainite which forms about 350 degree Celsius temperature. This is the upper Bainite. This is the Bainite which forms at 800, sorry, 278 degree Celsius temperature, lower Bainite. Morphologies are distinctly different. So, it is basically nucleation and growth phenomenon; transformation, again same; Fe alpha plus Fe 3 C, and it leads to relief effect.

You know, what you see in Martensites. Martensites, you know, if you, I do not know whether you have I talked about it, but, Martensite transformation leads to surface reliefs; surface will have relief of because of transformations; that is because of the strain. In this is also observed a bainitic transformation; that is why bainitic transformation is more complex. It has both of the Pearlite transformation and the Martensite transformations. Lower temperature carbides; they are observations. At lower temperature, carbide can be epsilon carbide, which I have discussed for the tempering of Martensites, and it can have about little less carbon, little more carbon, and 8.4 percent carbon. Bainite plates a irrational habit planes. Let us not discuss about it. Ferrite and Bainite plates possess different orientation relationship, relative to the parent phase. And, this is again taken from the book of Donald, Clark and varney; its references are given here.

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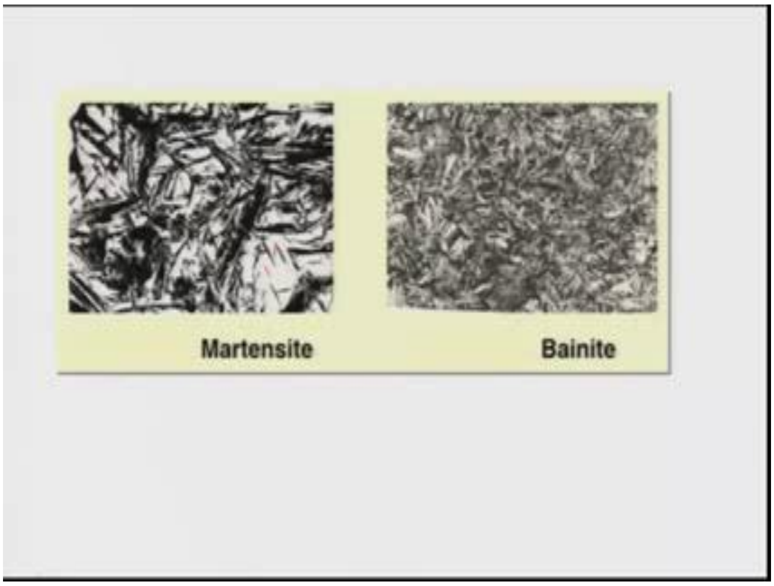

Now, I want to also tell you something; this sometimes, if you are looking a sample under optical microscopes, you will mistake a Bainite, like a Martensites; that is what is shown here. This is the Martensite, you see, and this is the Bainite. Difference is this; in a Martensite, there will be lot of retained austenite; and these are the white areas. These are the retained austenitic white areas. But in a Bainite, there is no such retained austenite; because, Bainite is more close to Pearlite, that is why, there is no retained austenite remains; all austenite transformed to Bainite.

But in Martensite, because it is completely shear dominated process, lot of change generated inside the matrix, or inside the austenite, and that is why some retained austenite is, austenite is retained; you cannot completely convert into Martensites that is because of the strain involved. So, with this, I just wanted to close on the Bainite transformations. Now, I am going to discuss on t t t diagrams in this class, for whatever time I have, and also, carry over to the next class.

So, you know, in industry, or in the real shop floors it is very difficult to tell them, what is Bainite, Martensite, or Pearlite. They may understand, but they cannot use this. And, it is not possible to see all this, go back, prepare a sample, polish it, make a sample for optical microscopy, and then observe it, and then find it out. So, therefore, what people have done is that, for each steel composition, there are transformation curves available.

And, these transformation curves are known as t t t curves - time, temperature, transformations. There are three ts.

First t is called time, which will be small t; but normally, we write capital T. Second t is called transformation, time, temperature, sorry; temperature; and, last, third t is called transformation; there are three. So, ideally, these are plots, and ideally, this will be three dimensional plots; time, temperature, transformations. Transformation will be percentage always, but normally, we do not do that; because, three dimensional plots are difficult to understand. Metallurgists are not good at.

In fact, I will not say that, but metallurgists have difficulty in understanding three dimensional plots, which we will see for ternary phase diagrams. You yourself have to realize that, it is not easy to, you know, to visualize the three dimensional diagram, and get some important thing out of it. So, that is why, you know, we use these two dimensional diagrams, in which the horizontal axis will be time, in scale; vertical axis will be temperature in degree Celsius, and transformation will be plotted like a percentage inside the curve.

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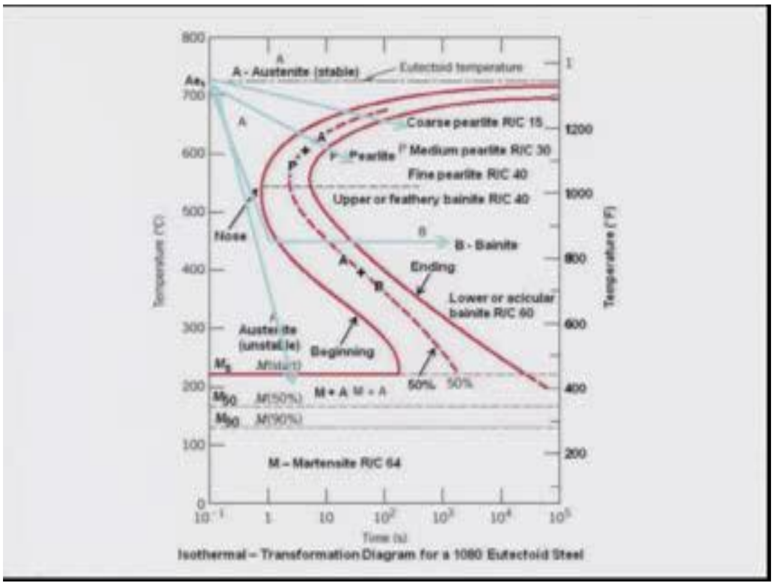

Isothermal – Transformation Diagram for a 1080 Eutectoid Steel

Let us, first, let me give you how the curve looks like. This is what it looks like. This is, you see, horizontal axis is time, and vertical axis is temperature; and percent transformation is given like beginning and ending. Beginning will be 1 percent, and ending will be 99 percentage. So, let me first go back, how these things are done. First, let me start, you know, basically, any transformation, whether it is a Pearlite, or Martensite, or Bainite, is obviously, transformation rate is what is very important. Rate means, how fast the transformation process is taking place. If you know the rate, then, if you know the time, you can multiply the rate with the time, you get amount transformed; that is very simple. Any mathematician or anybody who knows little bit of mathematics will be able to tell that.

Now, transformations rates actually depend on two things; obviously, nucleation data, and the growth rate, right.

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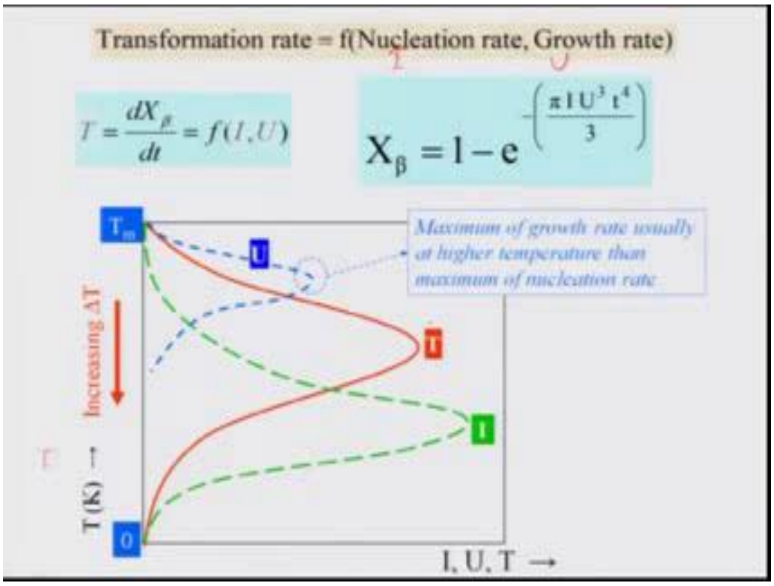

So, therefore, if I write T as a transformation rate, capital T, or let us write, you know, t dot; that is better; that very t dot, because, capital T is always represents temperature. So, that is basically nothing, but d X p, for beta phase suppose, by d x t. And, that is the function of nucleation rate, and the growth rate. Nucleation rate is represented by I; growth rate is represented by X. So, the classical jumps on equation which you do not know, but you can look at physical metallurgy book. It will tell you, for the Pearlite transformations, the transformation rate, or fraction transformed beta, is nothing, but 1 minus exponential by exponential to the power minus pi I U cube t to the power 4 by 3, correct.

So, now, if I now, you know, obviously, this depends on temperature; because I and U are temperature dependent. And, the nucleation depends on temperature, we know that.

Nucleation depends on free energy; free energy depends on temperature; growth also depends free energy available. So, these also depends on temperature; temperature in built. Now, if I plot temperature versus, you know, I, this is, sorry, this is the, these things U, I and t dot, these three things are plotted as a function of temperature. Temperature is plotted on the vertical axis, and these are all horizontal axis. Just to make you realize that, this is what is possible. Now, you should know nucleation rate; obviously, nucleation rate I am not discussed, but, let us understand that, nucleation rate, you can calculate nucleation rate. It depends on amount of nuclei available, multiplied by some exponential factor, which can be obtained from any physical metallurgy book, or, in the next class, if I have time, I will discuss with you.

Now, so, to make it short, I can say that, you know, these are all curves looking like a, you know, u shaped, inverted c shaped curve, correct. See the temperature, nucleation rate, growth rate. Now, if I, total transformation, it is integration of nucleation rate, growth rate; that is why you find this kind of curves. So, therefore, if I plot temperature versus this thing, they will look like this. Now, let us stop here. In the next class, we are going to discuss in detail about this, which I will do, and I will talk about it, the TTT curves.