# Phase Diagrams in Material Science Engineering
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## Lecture – 32
## Martensite Transformation – II

In the last class, I discussed about Martensite transformation. I started actually discussing on Martensite transformation in the steels. And, in this class, I am going to discuss in detail about Martensite transformations. As you know, I told you at the beginning that, austenitic phase can undergo three different transformations; depending on the way you cool a steel sample. The first one we discuss is about, about the Pearlitic transformation, in which austenite get transformed into pearlite because of slow cooling, below A 1 temperature. Second one, which we are discussing is, now, is the Martensite transformation, in which the steel sample from the austenitic stage is quenched in water, and thereby, leading to the formation of hard, brittle martensitic phase.

And normally, Martensitic steel is hard, brittle. So, the way Martensite transformation happens is that, the austenitic phase, which is F C C, presented cubic solid solution of carbon in iron undergoes shear induced diffusion-less transformation, in which the atoms get shifted by the application of shear force. And, that is what I discussed; again, I am going to show you for your information in the slides.

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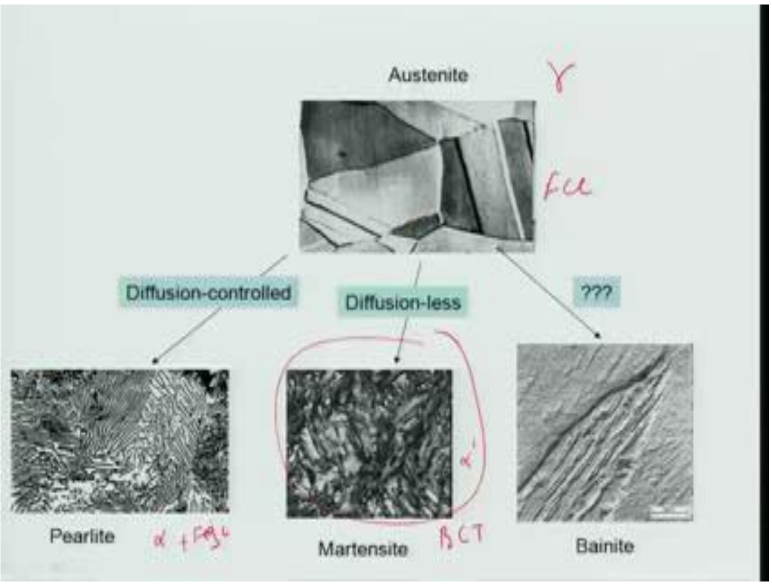

So, Martensitic transformation is basically a diffusion-less transformation in which the F C C austenitic phase, F C C austenitic phase get transformed into Martensite, what is, which has a crystal structure of B C T. Remember, austenite we term as a gamma; this Martensite, we term as alpha prime, and in Pearlite, we have alpha iron, or alpha plus Cementite; Cementite is Fe 3 C. So, Martensite is a single phase structure with a body centered tetragonal structure. Normally, the body centered tetragonal structure is defined by, based on the cube lattice, in which both the lattice parameter a and b are same; c is distinctly different; and the tetragonality is defined by c by a ratio, and here, c by a ratio is very small. It depends on the carbon percentage, but, it can be very small. But, low carbon concentration steel, it is basically, B C T, not a tetragonal, because c by a ratio is close to 1. So, this is the transformation which we are going to discuss in detail now.

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MARTENSITE

But, let me first show you some slides and pictures, so that, you get enthusiastic on the learning of Martensites. Martensite normally comes as 2 morphologies, as I told you; one is lath; other one is plate. So, lath and plate, and it happen that, in some cases, you get mixed of these two. In this picture, which is a optical micrograph, they can nicely, from the Professor S P Gupta’s book; you can see clearly, see the plates of Martensites very nicely; these are the plates of Martensites.

And, the white area, so, that you see is basically, retained austenite, which we will discuss later. They are retained austenite. Remember, this is a shear induced transformation. So, therefore, it involves straining of the matrix, and the strain means extra energy, and because of that, austenite is retained in the microstructure. We will discuss in detail later part, but, as you see here, Martensites comes a distinct morphology. It is not same as pearlite, austenite, or any other things in the steel. So, if you look at a microstructure of Martensite, under optical microscope, you can distinctly see, discern that morphology very, very nicely. So, this is what it looks like.

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**Martensite**

Now, if you look at a much hard magnification, as I told you, Martensites comes into two morphologies; one is lath; one is plate. So, these are the laths, you can see; you can see that, they are like leaves of the tree; different leaves. And, these are actually plates on the right side; you can see when the plates, within the plates, you can see even some, you know, dislocations, or defect structures, built in.

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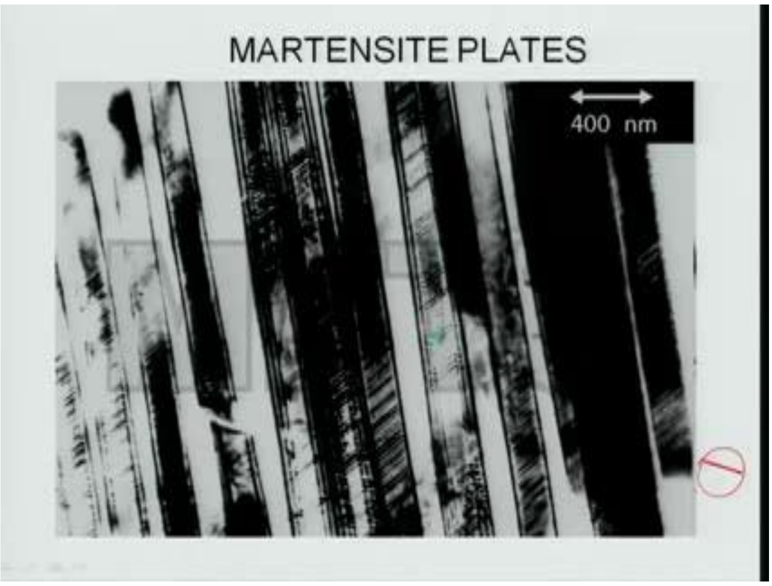

So, and most importantly, if you look at, under electron microscope, when these plates will look like a tree in morphology. I do not know, you have ever seen twins in copper grains. Normally, this is a copper grain twin, runs parallel to the grain, from one grain boundary to other grain boundary, like a plate. So, these are all the twins you see here, twins. So, inside each of this martensitic plates, you can see twins very clearly. and, this twin is basically because of the retaining the habit plain in the, in the Martensite transformations, in order to retain the habitment undistorted, we need to have a twin, or slip kind of deformation inside the plates, and that is what is visible in this microstructure.

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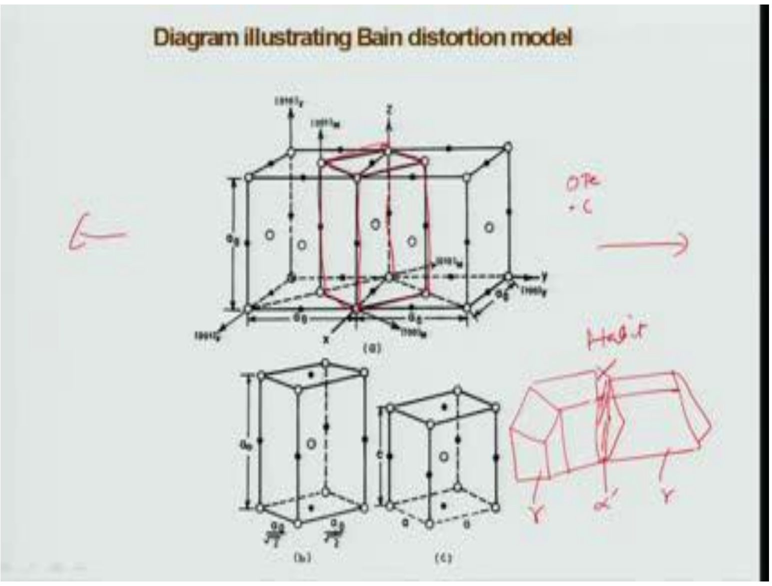

Diagram illustrating Bain distortion model

Well, the way things happens is, the transformation happens is, was first time explained by E C Bain, b a i n, not brain; E C Bain, long back actually. And, this is known as, also known as this Bain distortion model. I discussed in the class, I am going to show you in, in the board last class, and I am going to show you on the lecture slide now. If you consider 2 F C C unit cell, 2 F C C means, 2 gamma iron; as you see here, 2 F C C unit cell here. And, they are side by side.

Now, you know, this F C C unit cell has a lattice parameter of a zero. So, this can be actually, you can generate the B C T unit cell from these 2 F C C unit cell like this. This is the one I am drawing by using a red color; you can see here, this is the, this is what is the B C T unit cell. Here, the atoms are at the each corner of the unit cell, and there are atoms in the center. So, these white atoms, the white, I mean to say the things which has inside is white is a iron, while on the other hand, these atoms, these black ones, are dots. These black dots are actually carbon. The carbon atoms normally stay in the, in the octahedral voids of the, this. So, from, by distorting this F C C unit cells, or F C C, you know, austenite, we can actually generate the B C T unit cell. And, this can happen by application of shear force; it do not require any other things. So, what do actually happens is that, iron atoms in the lattice, they, both iron and carbon, but carbon atom undergoes larger distortion; they get shuffled because of the distortion.

So, if you have a series of the, suppose, series of this unit cell surface, and from one, this end to this end, the large number of unit cell present, each of this unit cell gets just rotated from F C C orientation to B C T orientation. And, this orientation change is very, very fast. This can happen at the speed of sound, as I told you in the last class. So, speed of sound inside a normal iron is, normal, you know, the metal is very high. So, that is why, the frequency at which it happens is very fast, and this is the reason if you quench in water, immediately, this F C C austenitic phase transform into Martensites.

As you know, the bottom, I show you the lattice parameters of this B C T unit cell. See, the c axis is a zero, and both a and b axis are a zero by root 2, a zero by root 2 from the origin, where a zero is the original lattice parameter of the F C C austenitic phase. And, you can actually think about like this; you can draw this as a (Refer Time: 07:55) cover like this; this is, what is this? A unit cell, so in this whole process, what happens, the c axis gets compressed by about 20 percent; while on the other hand, a, the x and y axis in which the 2 a are written, they are getting, they are undergo tensile deformation about 12 percentage; that is what actually happens. But, you know, in the whole process, there is, before I go there, in the whole process, what actually happens in the, if I, I have drawn in last class; I am going to draw it here again, to show you that, these are the 2 austenitic unit cell, suppose. And, so, and, this is the, this is the plane which is undistorted, and remains like this.

So, I am just showing exaggerated distortion; this is the plane which remains, this is alpha prime, or Martensite; these are the gamma. So, this is, in a nutshell, these 2 austenite planes, just like that, I have shown you in the picture on the top. Here, this plane of Martensite remains undistorted. This is known as habit plane. Why it remains undistorted is still not clear, but it remains undistorted. And, and undistorted, un-rotated, and to keep it undistorted, un-rotated, you need to disturb, or you need to distort the other parts of this, of this, of this, you know austenites, of the both sides of this plane; because, you need to have, you need to keep this undistorted thing. Remember, this is a lattice invariant transformation. What I mean to say is that, one of the, there are 2 strain here. One strain is the plain strain, in which these transformation happens from F C C to B C T; that is what I discussed in the beginning. The rotation of these unit cells, from the F C C orientation to the B C T orientation happens by this plane state mechanism.

On other hand, in order to, you know there is another strain which is required to keep the habit plane between two austenite; austenite grains; undistorted. You may ask why we need habit plain. Well, in all martensitic transformations, this is has been observed, this is a real observation, experimentally, that one of the planes in the Martensite remain undistorted; and, that plane is called as, considered to be habit plain. So, to keep this undistorted habit plane, you need to disturb, or you need to destroy the remaining, the neighboring grains, and neighboring unit cells. And, this is normally done by twining a slip, and that is why, we observe twins inside that martensitic plate; that is very, very common. So, that is also very important, and I should iterate. So, this is very important, you need to understand that.

So, now let me just show you the few things.

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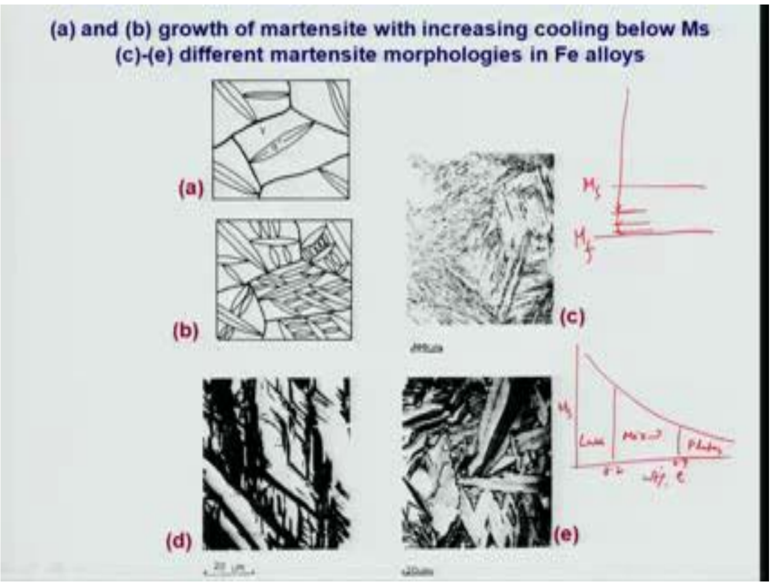
(a) and (b) growth of martensite with increasing cooling below Ms

(c)-(e) different martensite morphologies in Fe alloys

Let us first see, so, how defined morphologies do develop. Now, you know, this is what is these plates which you see here, very nicely. Sorry, these are the laths you see here nicely. What you see here is that, within the austenite grains, the Martensite, or alpha prime, this lath, originates. They form from one, one end, and grow in this other ends. So, each, each of this grains, you see the martensitic plates, laths forms, and that is why the second microstructure developed. And, this is what is shown here. This is what is shown there, see picture c.

Now, you can also have a plate that is what is shown here. These are the plate's morphology, which I have shown you earlier also, these are two morphology which is normally seen. Now, actually, this plate and mixed morphology depends on carbon concentration. So, if I plot a mesh versus carbon concentration, weight percent of carbon, that is the, normally, that is the normally the way things are done. So, and this, you can see nicely here. So, if I draw, that should increase the carbon concentration; Martensite transformation start temperature decreases, which I told you in last class. So, normally, low carbon concentration, you see lath and high carbon concentration, you will see plates; and in between, you see mixed morphology. This low is about 0.2, and this is about, saying, 0.7, or, 0.8; that is how the things happen.

So, that means what, as the martensitic start temperature decreases, or drops, there is a tendency of formation of this defined morphologies. Ok, now, let me clarify that, you know this Martensite transformations is a thermal in nature, as I told you in the class, last class. Why, because, this transformation depends on the 2 temperatures, martensitic start temperature, martensitic ends temperature. When you will discuss about the t t t curves, we will show how this temperatures will depend on, and what are the ways we can actually generate t t diagrams. So, martensitic start temperature is the temperature below which the Martensite can start forming; whereas, martensitic finish temperature is what is the temperature at which martensitic formation is finished, or over.

So, in between this temperature, you need to cool the sample rapidly; then, all this transformations happens. But, you know, once you cool the temperature, the steel, suppose this is a m s temperature, start temperature; this is a m f temperature, or finish temperature, and this temperatures as very close to room temperature; may be 100, or sometimes even less than room temperature. So, by cooling the steel till this temperature, now, the transformation of Martensite will not depend on time anymore.

That is obvious, because, martensitic transformation is, happens at speed of sound. So, therefore, it will happen immediately. So, that is why, it is thermal; it does not depend on time anymore; it depends. So, if you, at this temperature, whatever about Martensite is required to transform, is transformed, and then, it will remain; rest of the austenite will not transform. Then, if you cool it further, some more amounts will transform. If you cool it further, some more, and finally, it will be over at the m f of temperature.

So, whatever way you do, because martensitic transformation requires strain, straining the matrix, straining the austenite, as you see in the formation of twins, formation of dislocations, in the microstructure. So, these strain energies, whatever strain energy is present in microstructure, this is what I show you in the last class; this is strain energy; you see the twins there; you see the plates; there you see the dislocations. This strain energy is going to make the transformation of remaining of the austenite more difficult.

That is obvious, because, strain energy is a positive energy. So, if you quench from the austenitic state to the very low temperature, at room temperature, like quenching in water, you are going to give a huge driving force for martensitic transformations. But, you know, out of available driving force, a majority part of the driving force is spent in straining the matrix, or straining the creation of this deformation, or creation of the twin dislocations. And, because of that, the more large amount of this, the available (Refer Time: 14:54) energy is spent, and as you create more and more deformations, more amount of energy is required.

So, finally, what will happen, whatever initially energy I have, for making this transformation to happen, the finally, as a deformations goes on, (Refer Time: 15:09) transformation, the energy getting reduced, that is why, you finally retain some retained austenite, you cannot do any transformation. Industrial scale, what they do normally, to transform the retained austenite; retained austenite is very dangerous, if it is remain in the micro structure. Why it is dangerous, because, it will have all the tensile stress built in, inside the retained austenite. And, because it will retain the tensile stress inside it, the moment you apply the material, it will crack; that is what is observed in many martensitic transformation, transformed steels.

So, in order to reduce that cracking tendency, retained austenite must be removed from the micro structure. So, that is why, industry, many times they cool, cool it to the liquid nitrogen temperature, so that, all the retained austenite transform; all the 99 percent retained austenite transform to Martensite. There is no retained austenite left over. This is one such thing, like, if you see this picture, here, a lot of retained austenite is retained; as I am putting my pointer on that, these, these kinds of things are basically martensitic laths. But, on the other hand, this grey color, the magenta color thing is basically martensitic (Refer Time: 16:09) austenite. And, which is very, very predominantly observed in the microstructure. This is very, very unique in the, in the microstructure. So, it is important that, we do not keep any retained austenite in the microstructure. But, you cannot avoid (Refer Time: 16:22) transformation process; that is what is the, the important aspect you must take care; the retained austenite is not at all required in the microstructure.

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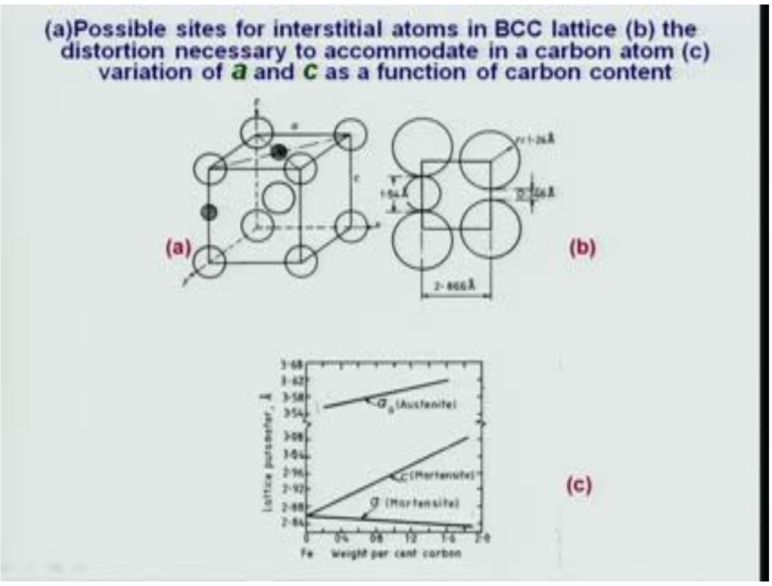

**(a)Possible sites for interstitial atoms in BCC lattice (b) the distortion necessary to accommodate in a carbon atom (c) variation of a and C as a function of carbon content**

So, now question is this, you know, when you transform this, the Martensites, as you see here, the, I am showing you the martensitic lattice parameters. This is the lattice parameter of the, this is the lattice parameter function of carbon concentration. This is lattice parameter of the austenite. It does not change much, as you increase carbon concentration; because, the F C C lattice carbon can easily go into more and more, but in b c c lattice, in B C T lattice, it cannot. So, the change of lattice parameter from 3.55 to 3.6 is what happens, if you increase carbon concentration from 1.2 to 1.6, or 1.7.

But, Martensites, a and c axis, they behave differently. The a, the lattice parameter of a will decrease as a function of carbon concentration, quite a lot, from two point, you know, 2.85 to about 2.8. On the other hand, c axis undergoes a massive change from about 2.85 to about 3.8, as the carbon concentration increases from zero to about, you know, 1.7. So, this is another important aspect; so, that means what; as c axis is keep on increasing, as the carbon concentration increases.

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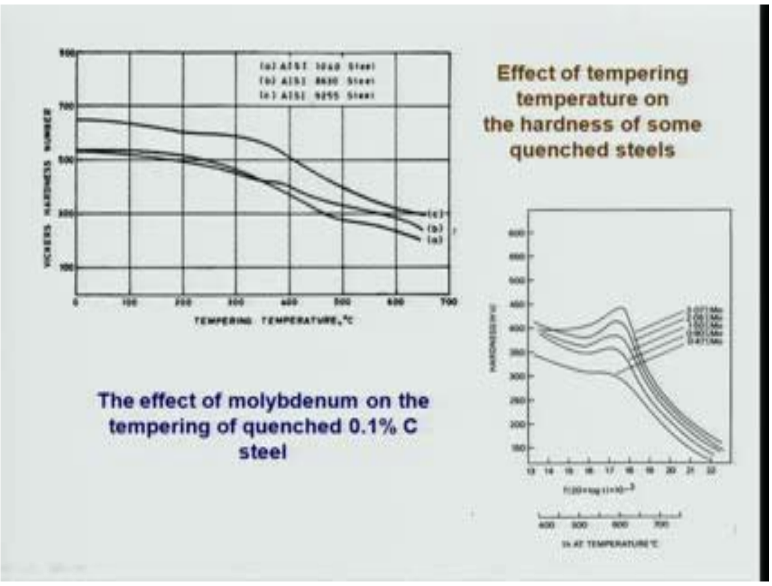

Effect of tempering temperature on the hardness of some quenched steels

The effect of molybdenum on the tempering of quenched 0.1% C steel

Now, not only those, the other elements also do have a strong effect in the martensitic transformation. In fact, if you add alloying elements like stainless steel, if you add chromium, nickel, some other alloying elements like moly, the martensitic start temperature actually increases, as you increase, as you increase the amount of the alloying elements, and that has been seen. So, the hardness increases, as you keep on increasing the, this alloying elements, because, this alloying elements imparts more solid solution state into the Martensites.

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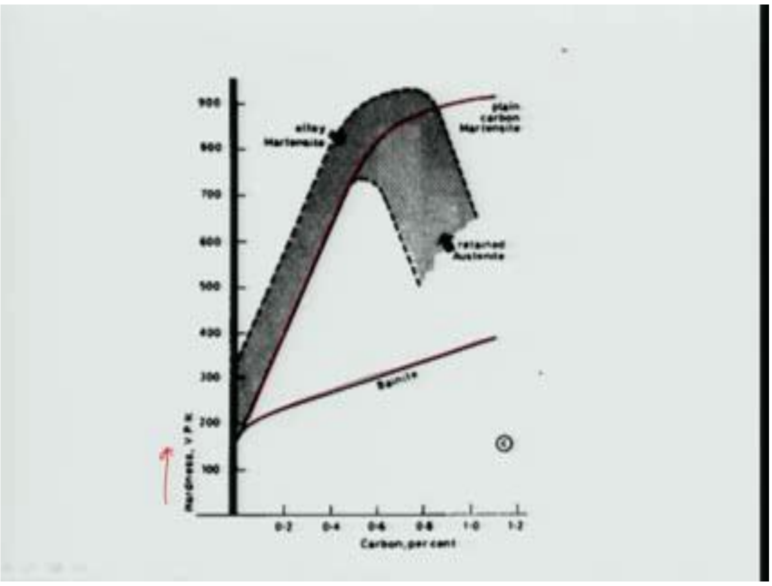

Now, Martensite strength also depends on carbon concentration. This is the hardness plot as a function of carbon content. You see here, this is the Martensite. This is the Martensite for the plain carbon steel; I am just showing this is the Martensite for the plain carbon steel; just keep on increasing beyond point, up to 0.6, or 0.8, then, it remain saturated. So, that is what happens; so, that means, more the amount of carbon, more is the amount of, amount of strength in the Martensites. On the other hand, we will discuss Bainite. Bainite, it does not change much. It remains, is varies from 200 to 400 v p n, not much. But, there, it can go up to 900 or 1000 v p n very easily. So, in the, in the Martensites, as I told you, Martensites actually is what? Martensites are very hard, and very brittle; I told you that.

So, normally Martensites are not directly used in the, in the applications; although, martensitic transformation is used for, to generate different microstructure. But, we do not use a component which is completely transformed into Martensites, just because it is very brittle and very hard. Hardness can be as high as (Refer Time: 19:19) hardness; it can be as high as 60. So, what is needed to reduce this brittleness is tempering the Martensites. Tempering means, you know, to reduce the brittleness by some heat, subsequent heat treatments. So, if you heat the Martensites, at high temperatures, they undergo certain transformations; because of that, you can actually create a different kind of microstructures. So, in this, this transformation switch, I will discuss in the class, in the, in the lecture in the next few things, in the next lecture, but before that, let me just tell you few other things about Martensites.

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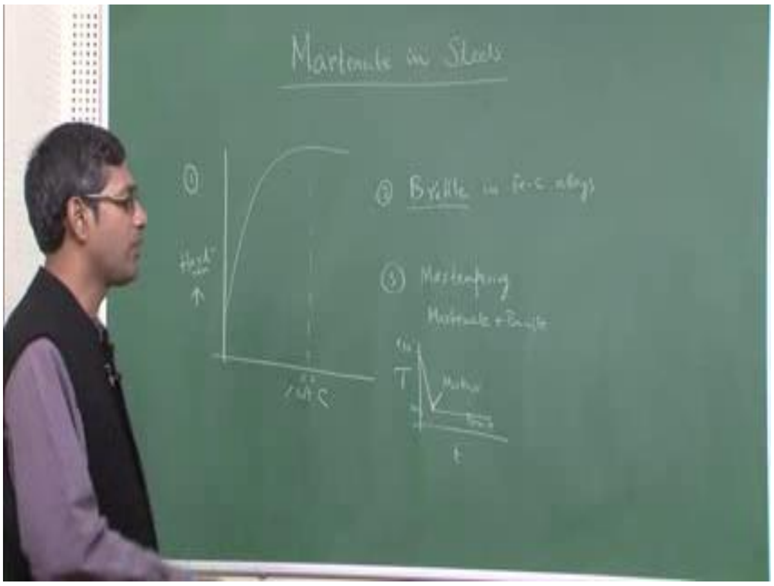

As I told you in the class that, Martensite strength is depends on the carbon concentration. If I plot hardness, I showed you that, in the, in the carbon, in the, in the slides. So, as you see, Martensite strength increases; this is our 0.6 percent carbon, 0.8 percent carbon. Then, it remains flat. Why does it happen? That is because, if you put more and more carbon into the, into the, into the b c t lattice, it distort the lattice more. and, and, it reaches an optimum level about 0.6, or 0.7 percent carbon, beyond which, it cannot take any more carbon.

So, whatever remaining carbon is there, if you add into the, if you take a steel with 0.8, or 0.9 percent carbon steel, the remaining carbon concentrations will not add up into strength of Martensites. So, that is why, you know, normally, martensitic transformations are good for the mild steels, about 0.3, 0.4, 0.5 percent carbon steel. Martensitic transformation will not change strength of the steel much, if you increase carbon concentrations from 0.6 to 0.8, or 1 percentage. So, that is another thing which, which you should incorporate.

Second important thing is that, the Martensites are, as I told you that, they are very brittle, and why they are brittle because, it has lot of strain inside it; lot of twins, dislocations which are there, the moment you apply force, it cannot no longer deform plastically; because, it has already lot of strain inside the matrix, inside it. So, that is why, they cannot anymore, take up anymore strain, and because of that, the strain, the

Martensites will be brittle. So, but on the other hand, there are Martensites, like in iron nickel, you know, there are some (Refer Time: 21:37) alloys, the Martensites is basically not a brittle, it is ductile.

As I told you, there are many nonferrous systems also, where the Martensites is observed. The (Refer Time: 21:46) is one such system; copper, nickel, aluminum, copper, manganese, aluminum, is where the, this martensitic function is also observed. There actually, the Martensites is ductile. So, we just find this is why they are ductile, and that ductility of Martensite can be used to give shapes in the (Refer Time: 22:01) alloys, this is done. So, logic, what is used in steel cannot be directly used in the non-ferrous metals. So, because, this is brittle in the steel, so, they are brittle in, in iron carbon alloys, or steels, iron carbon alloys. So, therefore, this needs to be, you know, treated, and that is what we are going to discuss in the next class, in a detail manner. But, just I want to tell you the reason why it is brittle, because it has a lot of strain inside it. So, that is, that is the second important aspect.

Third important aspect is that, you know martensitic transformations actually, as I told you, it is very simple. You take steel, and quench in water, or liquid nitrogen, or oil, you can transform into Martensites. But, there are situations where you can actually get both martensitic transformations, and the, (Refer Time: 22:48) transformation together; there are steels actually, it possible there. You do not need to quench into water, at low temperature; you can quench it to oil, which is kept at very high temperature, 300, 400, or, 300, 250 degree Celsius temperature. So, as you quench from, from very high temperature, to 350, 300 to 250 Celsius temperature, initially, some amount of austenite will transform to Martensites, but then, whatever austenite will remain, that will transform into bainite, which we will discuss in the subsequent lectures.

So, this is sometimes known as martempering. So, it is not same as tempering. So, martempering is martensitic formation, and bainitic transformations, Martensite plus Bainite. So, you can actually tell a, take a steel sample; this is temperature; this is time. So, you can rapidly cool up to 250 degree Celsius temperature; this is 250; this is 950; rapidly cool and keeps it there. So, because of rapid cooling (Refer Time: 23:55), Martensites forms, and then, in this part, we will have bainitic transformations possible; because, you keep it at high temperature.

So, you have a microstructure which, this is also known as; this is also, you know, very important tool nowadays, to create different kind of microstructures. So, that is all for the, for this formation of Martensites. In the next class I am going to discuss about the basics of martensitic, tempering of Martensites in detailed manner, and if time permits, I can even start the bainitic transformations there.