Phase Diagrams in Material Science Engineering
Prof. Krishanu Biswas
Department of Materials Science and Engineering
Indian Institute of Technology, Kanpur

Lecture – 28
Austenite to pearlite transformation in Iron-Carbon phase diagram

Today, we are going to discuss detail about the austenite to pearlite transformation and subsequently, I am going to talk about the phase transformation for the hypo and hyper eutectoid steels.

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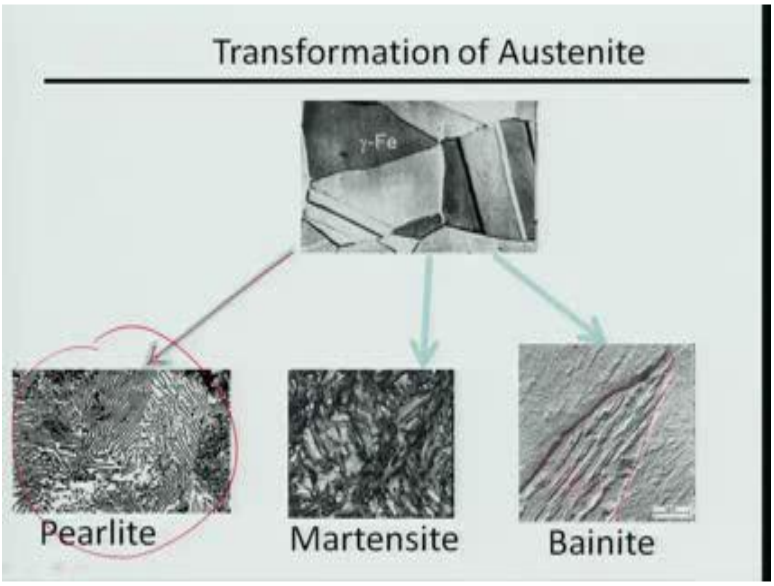

As I discussed in the last class, that we are going to follow this part, that is, how the austenite transforms to pearlite. As you know, austenite is a FCC solid solution of carbon in iron, which is stable at high temperatures, something like above 727 degree Celsius temperature, which is known as A1 and as you cool it down below 727 degree Celsius per eutectoid steel, you will get a phase mixture of alpha and the cementite, which forms like a lamella morphology and this is what is shown in this picture, and we have been discussing about these for the last several lectures.

So, I am going to just tell you, I am going to just tell you what actually happens during transformations.

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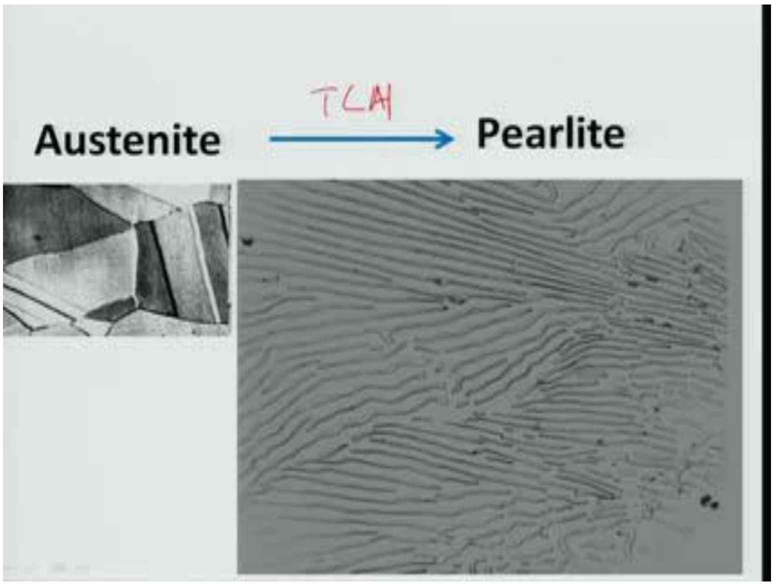

So, this is austenite and the pearlite. As you know, pearlite consisting of alpha iron and Fe 3 C and we will see how to calculate even the volume fraction of this in the, using the phase diagram there are today.

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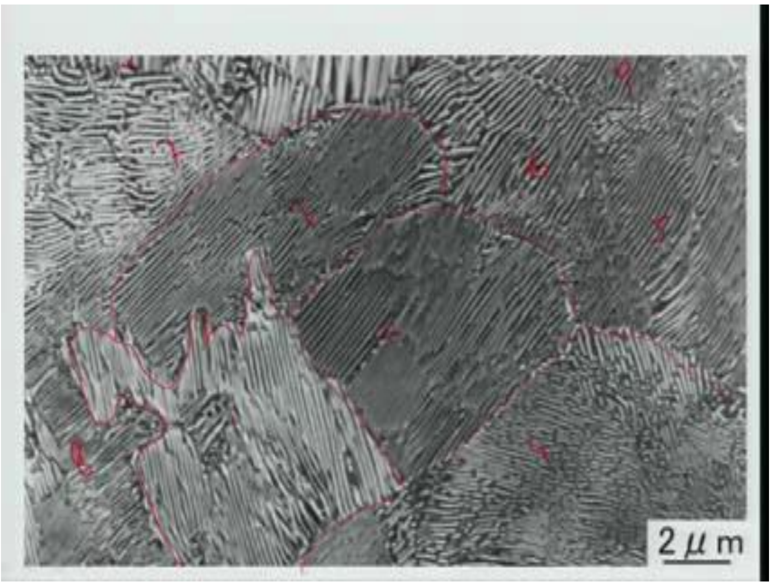

And I also showed you, that pearlite forms like colonies in just similar to eutectic transformation in the liquid to solid phase diagrams and each one of these, this is colony 1, 2, 3, 4, 5, 6, 7, 8, 9, even there are 9 colonies or even you can say, 10 colonies presence here. So, this is the way, the, the pearlite looks like, as you see from this picture is the luster of the pearlite, is just like a pearl, and that is why, it is called a pearlite.

And I told you in the last class how this transformation actually happens and we will discuss in more about details today.

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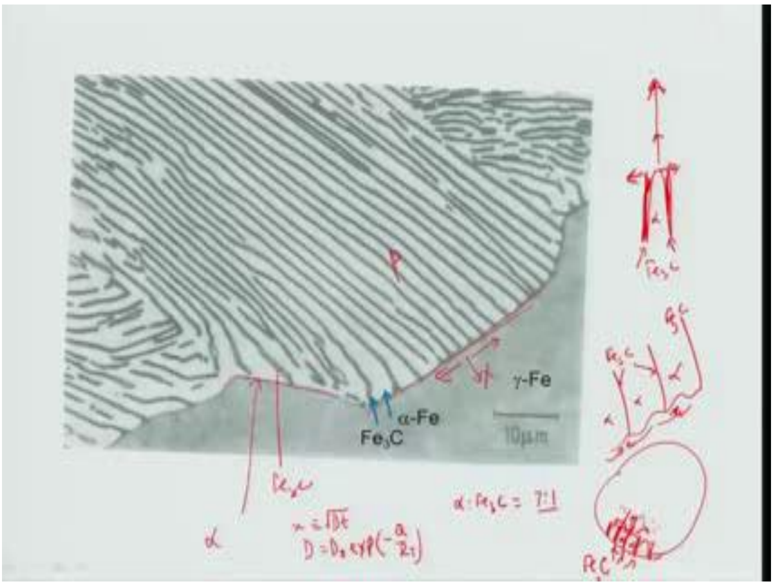

So, basically this picture, which was taken from the book of Making, Shipping and Treating of steels by U.S. Steel Corporation, tells you actually the fact very clearly. As you look at it, this is a curve formed between the pearlite; this is pearlite P and the austenite or gamma. So, between these this is a curve font and this font is moving or sweeping across as the time progresses and this was obtained in a very nice experiment very clearly showing, that how the austenite is getting transformed and forming pearlite consisting of alpha iron and the cementite.

Black ones are cementite and alpha iron, this if you look the interface very carefully, it is like this. So, this is Fe 3 C and this is alpha, alpha, so this is also Fe 3 C. So, these are all Fe 3 C in alpha. So, an interface is a curved one and many times it is a jagged interface. So, and Fe 3 C 2 alpha and (Refer Time: 03:30) is basically 7 is to 1, which I will show you. This is alpha to Fe 3 C volume percentage in the, in this, in this microstructure and it is all in the case for eutectoid steel.

So, how the transformation actually happens? That is very simple, let us look at the things here, I am going to do in the board, but I am going to show it here nicely. So, let us suppose, in one of the grains, which I have shown you in the last slide, that one of the phase (Refer Time: 04:00) cementite nucleus. It does not matter how the cementite or alpha nucleate, things will happen same. This is cementite, which nucleates and, and this cementite, basically Fe 3 C nucleates and Fe 3 C actually grows. As you know, Fe 3, Fe 3 C contains about 6.67 weight percent of carbon, which is much larger than the carbon concentration of the austenite grains for the eutectoid steel, that is. 0.8 percent.

So, all the, this whole grain would have carbon concentration about 0.8 percentage, weight percentage, but austenite, but the cementite, which is formed just now inside this austenite grain has a carbon concentration of 6.6 weight percent of carbon. So, because of that it needs lot of carbon. So, how does it get the carbon? It takes the carbon from the nearby region, this region, this region, this region, all actually feed carbon for its growth. So, then, then only it can have this composition, maintain iron and 6.6 weight percent carbon.

So, once it has pulled all the carbon from the nearby region, which is required for its growth, the nearby regions will be depleted of carbon and because of that depletion of carbon, nearby regions, because of depletion of carbon what will happen is, the nearby regions will become, will become lean in carbon concentration and because of that, sorry, because of that this will lead to nucleation of the alpha phase on the both side. This is alpha, alpha on the both side because carbon concentration has reduced so much, so nearby regions that it can even have very low carbon concentration, as close to, at .028 percent of carbon, which is required for the alpha to grow.

So, you know, any, so that this, what happens actually, as the alpha iron grows it reaches carbon, it reaches carbon in front, in also side wise and this carbon can then enrich the nearby regions, this regions, this regions, they can have a sideways transfer of carbon atoms, and this leads to again nucleation of this cementite on this side because carbon concentration will increase. And all this carbon concentration increase will lead to nucleation of the austenite or nucleus cementite and finally, again cementite growth requires lot of carbon so that our carbon will be lean in this region here, and alpha iron will be nucleated and grown. And that is how, this whole colony will form and this colony will grow subsequently further nicely and form big colony like this; that is how the things happens.

So, now, but in this situations, as you know, the alpha and the cementite grows carbon atoms, can easily diffuse from alpha to cementite, okay, alpha to cementite, alpha to cementite and these transport of carbon atoms or diffusion of carbon atom is basically happening edgewise, they are not happening across. Suppose this is alpha, this is not happening in this direction, they are happening in this direction, edgewise direction, that is, parallel to the interface, they are not happening perpendicular to interface, this direction. Carbon concentration, carbon diffusion does not happen, but carbon diffusion happens along these two directions very easily and this is known as edgewise diffusion of carbon. So, as the edgewise diffusion of carbon happen because this carbon will be then used for growth of the cementite on the sides of the alpha, these are the two cementite lamellae.

So, you understood right, the basically the idea is, that carbon does not need to go, diffuse long, long ahead in this direction. It does not require, only thing required for its, for the growth of pearlite is that carbon should diffuse sidewise or edgewise along the interface to reach the cementite regions because cementite requires carbon, ferrite does not require carbon. So, ferrite will give away all carbon that is why, I do not require any carbon, it will give all the carbon and this carbon will be then getting the sinks of the carbon and sinks of the carbons are what? Cementite, cementite require carbon and this is easily happen if you have edgewise diffusion and this edgewise diffusion requires basically solves two problems nicely.

One, edgewise diffusion is very, very fast, why? The diffusion path is very small, from ferrite to cementite nearest lamellae is hardly a couple of, by now nanometers distance away or maybe, tens of nanometer distance away, mean they are growing nanometers or maybe hundreds of nanometers distance away, not more than that. So, the diffusion of carbon for that distance is very easy than diffusion carbon to microns, several thousands of nanometers away. The carbon diffusion along the, this edge, these directions required. So, that is why, the carbon diffusion is very fast and because of this transformation is also very fast.

Second thing it solves is, that is, solve the problem of growth of cementite. Cementite is a stoichiometric compound. It requires of exactly about 6.6 weight percent carbon for its growth. So, therefore, for it to grow it requires those amount of carbon to supply and this supply is very fast or possible nicely, the edgewise carbon diffusion happens. So, therefore, edgewise carbon diffusions are the diffusion of carbon along the parallel to the interface between the pearlitic, pearlitic font and the gamma iron. A gamma is basically, very, very successful to make the transformation moving very fast. This is something which you must remember and that is why, the pearlitic transformation is basically quite fast.

Now, another important aspect, you know, this transformation is also depends on amount of undercooling it from height. Obviously, this transformation will not happen at 7, exactly at 727 degree Celsius temperature for eutectoid steel, why, because at 727 degree Celsius temperature for the eutectoid steel, there is no diving force available for the (Refer Time: 10:19) transformation to happen. At the temperature, the free energy of the gamma and the free energy of the phase mixture of austenite and, sops, cementite and alpha will be same. So, free energy of alpha and cementite mixture and the free energy of the austenite will be the same. What I mean to say is, that at 727 degree Celsius temperature for the eutectoid steel, the free energy of the product in the (Refer Time: 10:47) will be same. So, there is no difference of free energy, free energy difference is 0 and because the free energy difference is 0, the transformation cannot happen. So, therefore, the transformation to happen you needs to provide undercooling.

Undercooling is nothing but you cool below the eutectoid transformation temperature or below 727 degree Celsius temperature for the eutectoid steel and below A1 temperature for any other steel. So, if you cool it down below the temperature, then only you are providing the system a finite driving force for the transformation to happen and that final driving force is proportional to the undercooling. I do not need to teach you all this because these are all available in any standard textbooks. So, therefore, undercooling plays the most important role.

Now, you know, undercooling has a very funny role. First of all, you need to have a undercooling to provide the driving force for the transformation to happen, but if you are give, provide a very large driving force, suppose you cool down substantially, lower than the 727 degree Celsius temperature for the eutectoid steel, what will happen? Then, well, if you cool it down very fast, driving force will be very high because undercooling is large. So, transformation will happen very fast. But you know, this transformation requires movement of carbon atoms, transport of carbon atoms across the interface. That means, this transformation requires diffusion of carbon and diffusion of carbon atom is strongly dependent on temperature.

Anything diffusion depends on, strongly depends on temperature, why? Because diffusion of carbon atoms let us suppose, diffusion distance is, can be written as root Dt, x is equal to Dt. The distance travelled by the carbon atom during any diffusion of transformation can be approximated to Dt, where D is the diffusion coefficient of the carbon atom and t is the time you provide for the system to transform. So, as you know, D is basically temperature dependent, how it is, D is D 0 exponential minus Q by R t. So, it is a temperature dependent factor where D 0 is a constant or P exponential factor, Q is the activation barrier for the transformation, which is nothing, but diffusion barrier, R is individual gas constant and t is the absolute temperature.

So, as you undercool it more, your absolute temperature decreases. As the absolute temperature decreases, what will happen? Diffusion coefficient will decrease. So, therefore, diffusion of carbon atoms will happen slower, understood. So, as the diffusion carbon atom happens slower, diffusion distance will be slower. As the diffusion distance will be slower, the thickness of each of the lamellae will be slower, will be smaller. So, that means, it will create fine pearl like pearlite lamellae. That means the distance between the thicknesses of these lamellas will be smaller; means internal spacing will be smaller. So, therefore, as the internal spacing becomes smaller, the interfacial energy dips. The area between these two lamellae will be higher and because of that system will require more energy, correct. So, this is the negative effect of higher undercooling.

What is the positive effect of undercooling? Positive effect of undercooling is that system has a large diving force available. Because system has a large diving force available, system can actually spin the driving force to create, you know, more, more and interface. So, final lamellar spacing means more interfaces. So, those more interfaces will have most interfacial energies, surface energies and this interfacial surface energy can be accommodated by the driving force.

So, that is why, if you look at the transformation kinetics of these, which I am going to discuss on the board with now very soon, it depends, it basically interesting function of undercooling. It increases as you increase the undercooling initially, but then it decreases as you decrease the undercooling. That means if I plot undercooling versus velocity of the interface, it will have C, inverse C separate curve, that is what I am trying to say, and this has a very important role.

So, now let me go to the board and explain you in detail how things will happen.

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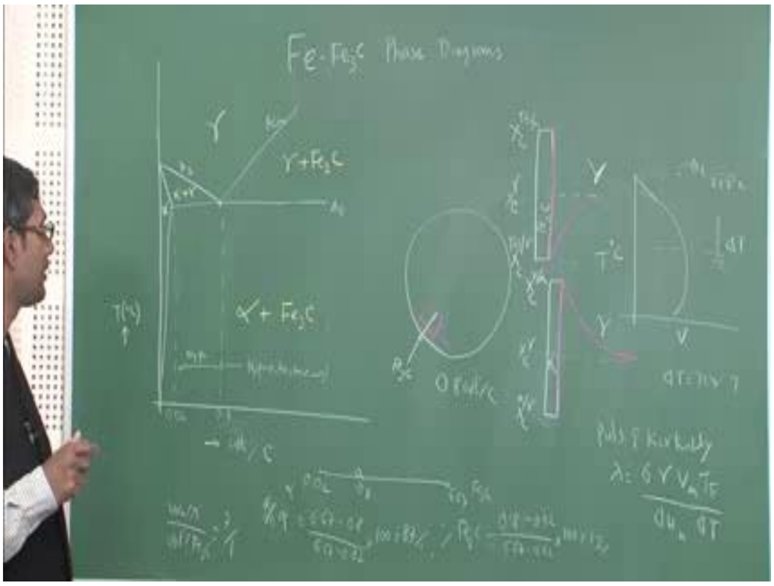

So, I will just try to use some composition profile for that. So, let me just explain to you again because this is a very important concept. Suppose, if I take (Refer Time: 15:11) austenite grain with 0.8 percent carbon and as I said, I just have a cementite nuclei to grow and cementite requires a lot of carbon, it takes the carbon from the nearby regions, all the places and because of that the cementite will be rich, will be taking all the carbon from this regions and the nearby regions will be depleted of carbon and that is what leads to formation of alpha. This is alpha, this is the alpha regions and this is the cementite.

Now if I plot the concentration profile across the cementite, how it will look like? Suppose this is my cementite lamellae, I hope you can see this, and this is my X C in gamma, this is X C in cementite, this is the compositional axis, this is basically a lamellae and this is X C Fe 3 C gamma interface. So, how it will look like? It will increase, it will be, it will be little bit like this; it will be very high at the interface. Let me draw by the color chalk. It will be very high at the interface, it will increase. The cementite will have a large carbon concentration, then it will go down and at the bulk it will reach the 0.8 carbon concentration that is why it will look like.

Now similarly, I can draw it for the alpha, how it will look like? Suppose, this is my, I think it is better I draw the side way, one is alpha, this is alpha, this is X C alpha gamma interface composition, this is X C gamma, this is X C gamma alpha, ok. So, now it, how it will look like? This is been like exactly opposite. So, this will, this is, X is equal to 0. This X, sorry, this is the interface, this will be like this. What does it mean?

The carbon concentration for the alpha when the alpha grows, that means, very clearly try to concentrate. When the alpha grows, carbon concentrations will pile up, just this side of the alpha or the side of alpha carbon concentration will pile up, and as you go long distance ahead, this is like this carbon concentration pile up and decreases. This is exactly like this, the way I have drawn, this is one such lamellae I am taking out and drawn. So, carbon concentration will be very high interface, it will build up because it, for alpha to grow carbon will be rejected. As the carbon, rejected carbon will be going up, increasing to very high value and then it will slowly drop in the bulk of the austenite grain. For the cementite, when the cementite grows, carbon concentration, cementite will require carbon, so therefore, nearby region will be depleted in carbon. That is what you can see here and then, the carbon concentration will be like this.

So, because of these gradients develop. This gradient, you know, this is large, this, this amount gradient developed, the carbon diffuses very fast from the austenite. So, these, both the sides are austenite, this is austenite, this is austenite, because of that the carbon will diffuse very fast into the austenite and because it requires higher amount of carbon. So, that is the basically how the diffusion of carbon will happen.

So, the take away message is, that for the pearlite growth diffusion of carbon is the most critical factor that I was mentioning in the last class and this is what dictates the, you know, transformation rate and everything. So, basically as I told you, transformation rate will be like this. If I plot the temperature versus velocity of the interface, it will be like these kinds of shapes. So, you can see, as you undercool it more and this is suppose my A1 temperature or 727 degree Celsius temperature, so it will be 0 almost here because there will be no transformation and it will keep on increase, increase, increase and finally, it will go to 0.

Final, it will decrease as the undercooling increases because this is the way undercooling is increasing. Undercooling increases as you go from this to this. So, the undercooling is defined as 727 minus T, where T is the actual sample temperature. So, the why this has happens? Very simple, and when your undercooling is very small, driving force is small. As driving force, force is small; the transformation will be very slow. But because at high temperature diffusion of carbon is fast, the lamellae thickness will be large, pearlitic, the lam, each individual lamellae of cementite and the, of the poly alpha will be very large.

But you know, as you increase the undercooling or decrease the temperature below 727, 727 degree Celsius temperature, what will happen? Because of the decrease of the temperature, the driving force is large. So, therefore it can create more number of interfaces between alpha and the cementite alpha and the cementite alpha and the cementite. So, for thickness of the lamellae will be small and the same that at the same time diffusion will be slower, why? Because your temperatures has dropped diffusion, as just now I discussed in the slide, the diffusion depends on temperature, temperature decreases, diffusion of carbon will be slower. So, distance it can travel will also be slower. So, that is why inter-lamellae spacing will be smaller. So, that is how actually the growth rate actually varies, vis a vis of growth rate interface, T is the temperature. So, as you increase the undercooling growth rate will varies.

Now, there is a formula given by Puls and Kirkaldy, Puls and Kirkaldy, Kirkaldy is very famous scientist and it says, lambda is equal to 6, they have calculated this gamma V m. I will explain the terms, delta H m, delta T. It is, this gamma is interfacial energy between alpha and the cementite; V m is the molar volume, molar volume of together; T is eutectoid transformation temperature, that is, 727 degree Celsius temperature; delta T is the undercooling and delta H m is the change of enthalpy per mole between the parent and the product phase, okay, the change of enthalpy basically when the, between the parent austenitic phase and the product phase, mixer of cement, cementite and alpha.

So, as you can see here, delta R goes to the denominator, that means what? That means, lambda is inversely proportional to delta T. So, that is why the inter-lamellar spacing will be smaller and smaller as you increase the undercooling. This, this is what is very important for you to understand.

Now, whatever time I have, let me just explain you the ratio of cementite and the alpha iron is 1 is to 7, why? Let us consider, this is, can be easily obtained from the lever rule. Let us consider the lever and let us consider eutectoid steel. If you have eutectoid steel, what will be the, what will be the lever? This is 0.02, this is alpha side, this is 0.8 on which we will put the fulcrum and this is 6.67, which is the carbon concentration of cementite. Now, if we apply the lever rule properly what is the volume fraction of, what is the percentage of volume of alpha? This is this some 6.67 minus 0.8 divide by 6.67 minus 0.02 into 100 and this will come like, 87 percentage.

So, what is the volume fraction of cementite? This arm divide total arm, this arm is what? 0.08, 0.8 minus 0.02 divide by 6.67 minus 0.02 into 100, this will be coming about 13 percent. So, as you can see here, ratio between this is almost how much? Yeah, 1 is to 6.5 or so. So, that is why it say, it is basically ratio between, if we assume this is volume percentage, if we assume densities of alpha and cementite almost similar, is almost same, it is called close to 7.8, 7.9, not much difference, will be there. If we assume that then the volume of alpha, volume percentage alpha and volume percentage of cementite will be equal to 7 is to 1. And if you assume that densities are equal, so then you can see the thickness of the lamellae, thickness of cementite and the alpha will be 1 is to 7. So, that is basically for the pearlatic transformation.

So, as you know, pearlite I have already discussing for the alloy with the, with the concentration of 0.8 percent carbon. For this alloy pearlite will be the only microstructure. I showed you a image of the large pearlitic colonies, 10 number of colonies I have shown. But I need to also discuss for the hypo eutectic, hypo eutectic alloys. This is the hypo and this is hyper eutectic alloys, hyper eutectoid alloys, what will happen? And I am going to discuss about that in the next class.

So, let us do that in the next class. And whatever I have taught you in this lecture are available in the book or even any internet literature you can find out these things and you should study. But the basically I am giving you a tip of the iceberg, the whole transformation mechanism as we started so nicely in the literature you can find many, many, many important aspects of this.