Material Science
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Lecture No 25
Transformations in Steels Eutectoid Steel (Contd.)

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We have seen the transformation diagram for this. And in the transformation diagram we talked about basically formation of ferrite and cementite and in the lamellar structure which we call as pearlite formation. Austenite is transformed to pearlite. The mechanism involves diffusion of carbon over some distance which is the inter-lamellar spacing between the middle of the ferrite plate to the middle of the cementite plate.

When the temperature is lowered further for transformation that we do a little faster cooling, the diffusion is becoming difficult for carbon and then transformation to bainite occurs, because the driving force or FCC austenite to go to BCC ferrite is very high, by some mechanism it wants to go to become BCC and that is why it is showed you in the last class how the FCC can become BCC. Actually it becomes BCT and if the carbon is not present there is enough contraction along the c axis it becomes BCC.

Then if we further cool at a still faster rate so the transformation takes place at a much lower temperature somewhere around room temperature then even bainite cannot form because this involves the diffusion of carbon, martensite is formed which does not involve any diffusion of carbon and that is what you have began to look at in the last class.

Student: (())(2:54)

Professor: Yes, not pearlite, cementite and ferrite but that cementite I told is not an equilibrium cementite FE3C, similarly the ferrite is not the equilibrium ferrite because you have got enough time for carbon to diffuse to longer distances.

Student: (())(3:12)

Professor: Maybe different, it could be different from there and it is not equilibrium.

Student: (())(3:18)

Professor: There is no carbon diffusing out, we are talking about that only today.

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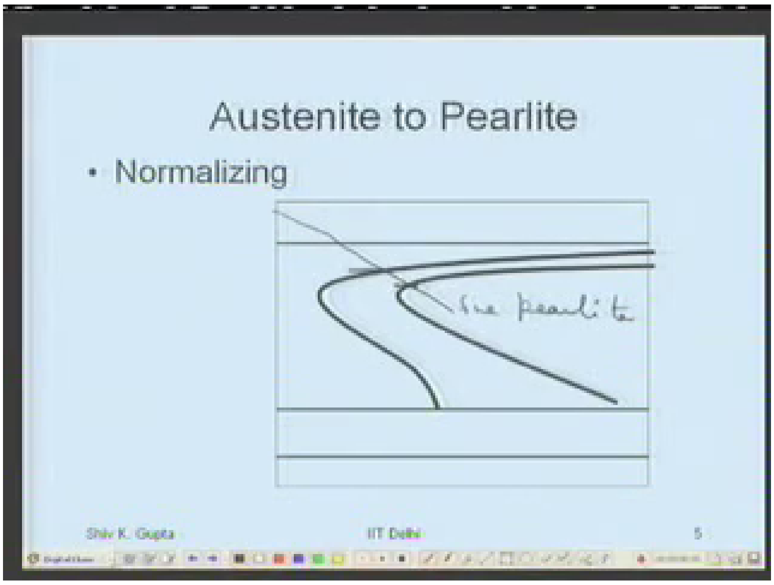

Where this picture of annealing where we do a very slow cooling and it is possible to form a coarse pearlite like this, a coarse pearlite is form in this temperature range. And when we do this cooling, faster cooling in air instead in furnace fine pearlite is formed because the nucleation rate is much higher. Here very fine pearlite is formed.

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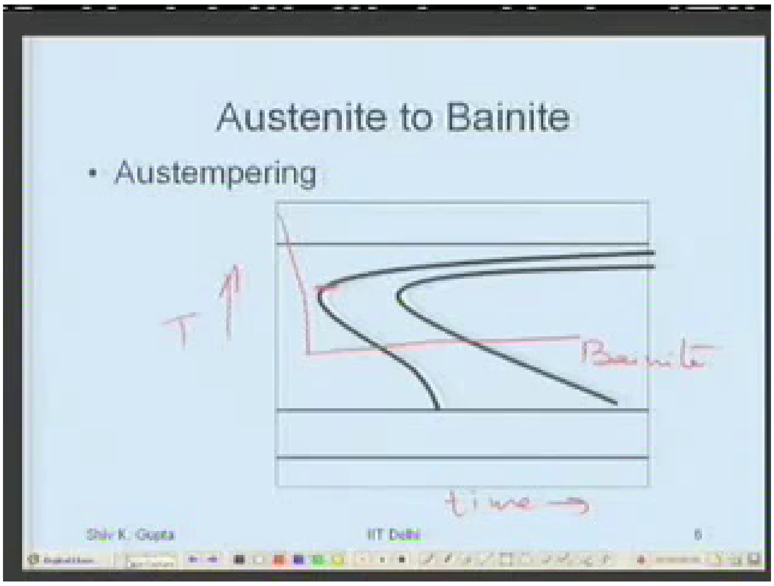

Then we saw that if we hold it, if I hold it, isothermally below the nose of the c curve what is referred to as a process of austempering that bainite is formed, you know this is your temperature axis and this is your time axis.

Student: It should actually come below of the c curve.

Professor: Yes, that is right otherwise the mechanism of pearlite begins here bainite cannot start. Once the pearlite has started, cementite has nucleated it in between the region would become ferrite because of the diffusion of the carbon, only this is these are finely placed. So once one mechanism begins the other mechanism cannot start and that is important into understand.

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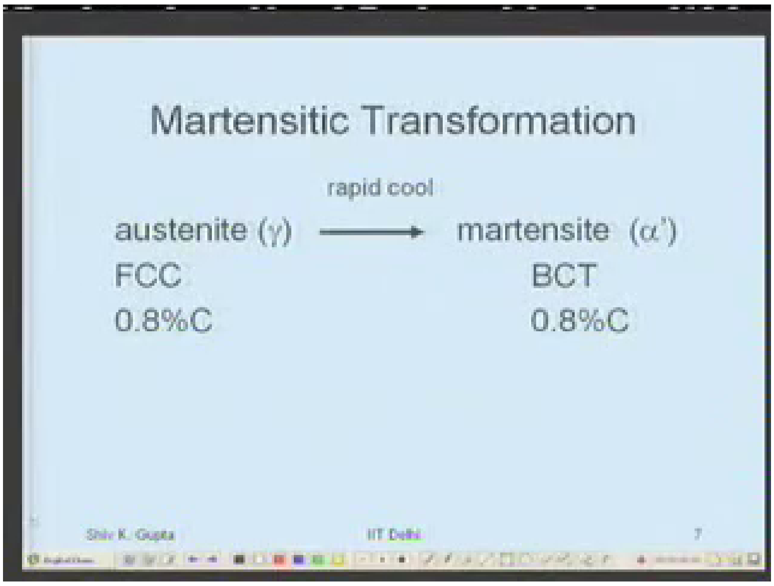

Now we are looking at the (())(5:23) transformation when I cool it faster, I don't hold it isothermally, just simply take it down to the room temperature while this martensite which is body centered tetragonal in shape all the carbon remain in the solution see that. 0.8% carbon was the solution is FCC, that remains in FCC and that is what is formed.

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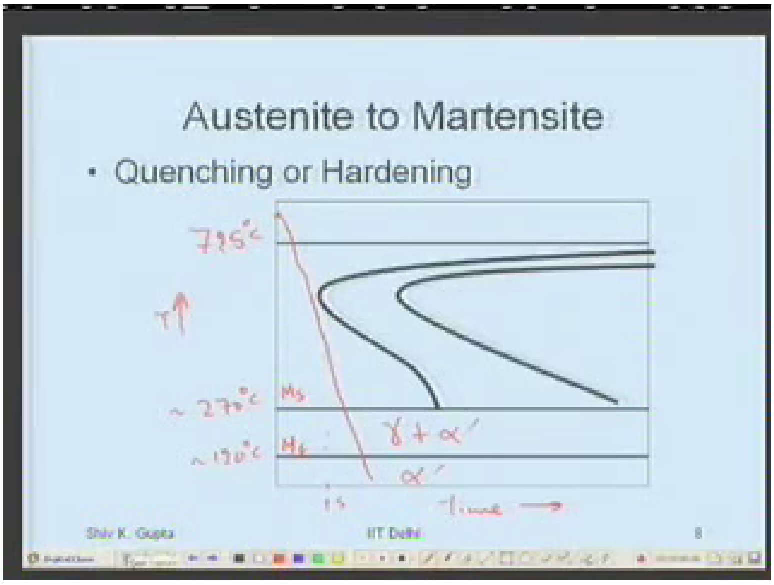

This is your temperature of 725 centigrade for this eutectoid steel, this time here is one second. This temperature I said is around 270 degree centigrade and that maybe around 120 degree centigrade for this steel. We quench is rapidly like this, I am not going close to the nose of C curve, I am not touching, not crossing to form a martensite. Martensite begins to form at this temperature which is 270 and finishes at this temperature, by the time it reaches room temperature it has already formed martensite.

And in this region I have both austenite and martensite, while I have here only martensite. So here we have not provided enough time for carbon to reduce, temperature where the diffusion is required to take place is very low, and carbon is enable to diffuse even though it is an interstitial mechanism of diffusion, it is a very slow process and it cannot take place.

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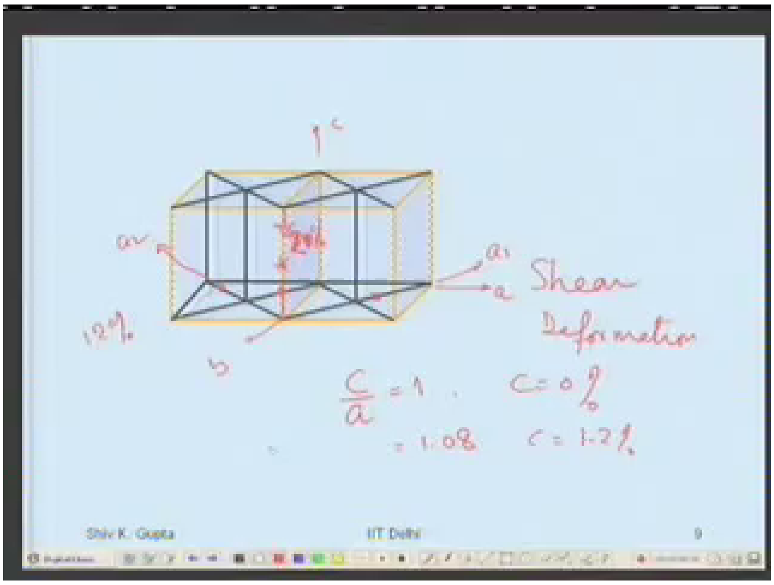

And therefore this transformation is brought about as I told in the last class by a deformation mechanism which is called a shear mechanism, while I consider this to be c axis, for the martensite this is the A1 axis, this is A2 axis, and if you want to name your FCC lattice you can call this as b axis and this as a axis, c remains c only thing is phase diagonals of the FCC becomes the A axis, B axis or A1 and A2 axis of the BCT matrix of the BCT lattice.

And here as I said I require contraction along these axes to the tune of 20% and I require extension along a1 and a2 to the tune of 12 – 13%. This contraction here is 20%. If the carbon is sitting here then it doesn't allow this to go down by 20%, it is not reduced by 20%, it reduces by less, so I get some tetragonality left Internet he matrix. As I said C by A is equal to 1 when carbon is 0, pure iron and this is equal to 1.0 A when carbon is about 1.2%.

And no carbon is able to grow out the matrix has transformed and it has the martensite but this kind of transformation does not take place simultaneously all over the volume and particles form either in the form of laths or they form in the form of plates. Plates are lenticular in shape and they cannot fill the whole space, where lath has a tendency to fill the space while the plates do not have. So as compared to the classical transformation austenite becoming ferrite and cementite what I call pearlite or another structure, another morphology of bainite where carbon is diffusing compared to that there is no change in composition in this transformation. 0.8% carbon remains 0.8% in the matrix.

Student: (())(10:34) You say that transformation has occurred when composition is different…

Professor: Not necessarily, transformation can take place when there is a change of composition, when there is no change of composition. When water freezes at 0 degree centigrade what is the change in composition but transformation has taken place, water has become ice.

Student: (())(10:54)

Professor: Yes, that is what it is, so there is no change in composition, you can also give rise to transformation.

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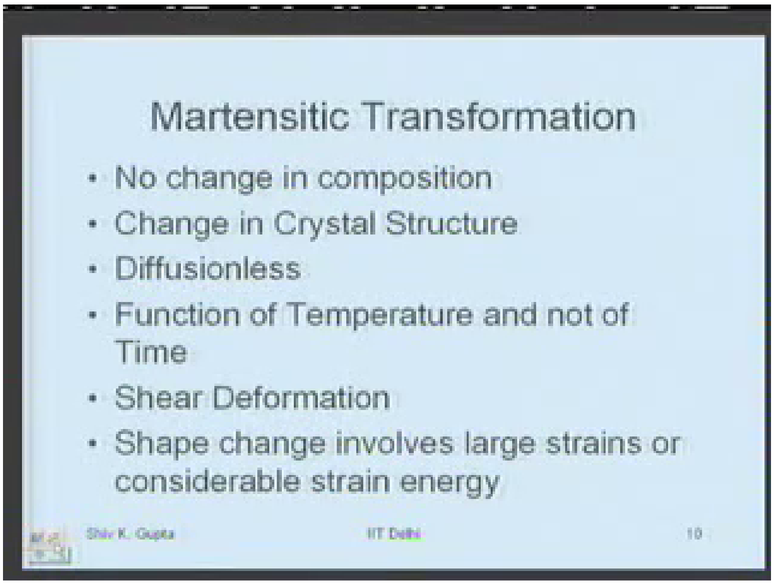

There is a change in the crystal structure, FCC has become a body centered tetragonal, there is a change in structure. Properties are vastly different, and there is a change in crystal structure, there is no change in composition but there is a change in crystal structure. A transformation is brought about by a diffusionless mechanism, there is no diffusion of any atom, iron or carbon, iron there is question vacancy mechanism is a very slow process.

Interstitial mechanism which is a faster process even that is not able to take place at room temperature and the transformation is brought about by the shear deformation therefore it is a function of driving force and not that of the time because diffusion is not involved, driving force has decreased in the free energy. For any process any transformation driving force is the decrease in the free energy.

Since I have come from 725 centigrade where there is a equilibrium where the change is 0, come to a lower temperature the free energy change would be very very high and that is what it is, so as particular temperature there is some driving force, more undercooling there is more driving force, still more undercooling still more driving force. So it is a function of temperature and not that of time of holding at that temperature because diffusion is not involved.

The mechanism is the shear deformation as I explained along with the three axis there is 2 axis there is an extension, 3rd axis there is a contraction and the shape change that involves gives rest large strain and therefore there is a considerable energy involved in the process. Driving force is going to provide that strain energy. Besides the shape change there is also a change volume involved. Matrix expand by about 4 – 5% when there is a transformation formed FCC to BCT or formation of martensite.

This 4 – 5% expansion if it is taking place in the whole volume there is no problem but it is not taking place in the whole volume, wherever the plate forms or wherever the lath form there is an expansion, if it doesn't form there is no expansion.

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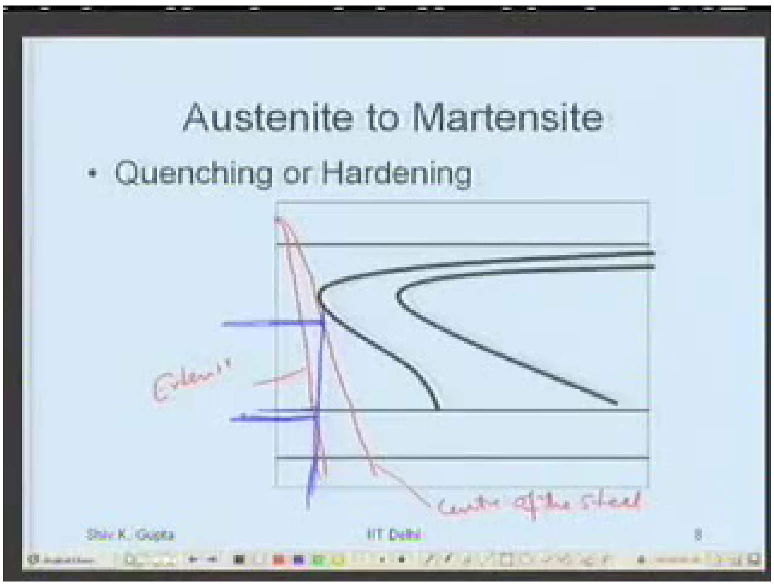

At the same time what is happening is when I quench from here surface of the steel is cooling at this rate, the interior of the steel will not cool at this rate, if I want to transform the interior to martensite interior should also be fast enough not the cross the nose of the C curve, so this is the exterior of the steel and this is probably the center of the steel. Then I am sure that it is going to be all martensite, even then plate cannot fill the whole volume so there is a retained austenite, plates are in lenticular shape, it cannot fill the space.

Laths which are shape of a ruler can fill the whole space. So we get about 100% or 99% martensite, it is when it is in the lath shape. When at the plate shape we don't get that much martensite. So interior must also cool rapid enough not to cross the nose of the C curve, if it crosses the nose of the C curve then interior is forming pearlite and the exterior surface is forming martensite. Second thing is when they act any given time let us I talk about this time, at this time this the temperature in the center and this is the temperature, sorry this is the temperature in the surface, surface has become martensite, the interior is still austenite.

This temperature is austenite, only this temperature some part of it has become austenite, the surface, the transformation is also not uniform at the same given time. Some part is transforming some part is not transforming, there is an expansion other place there is no expansion. In other words when the temperature is different thermal contraction, because I am cooling, I am not talking about expansion, I am talking about thermal contraction. Surface layers of cooling therefore they are contracting more, interior is not cooling, interior is not contracting.

In other words what I am trying to tell you is there is a differential expansion and contraction taking place which is not uniform all over the volume as a result there are large residual stresses developed in the material which sometimes can become so high that there is a cracking of the steel. I give you a plain carbon steel, ask you to austenitize it and quench it in water, invariably you will crack it. it will crack because of these large residual stresses which are developed and the material becomes brittle.

Cracks are the one responsible for making the material brittle and therefore our intention is to make it if possible the cry.

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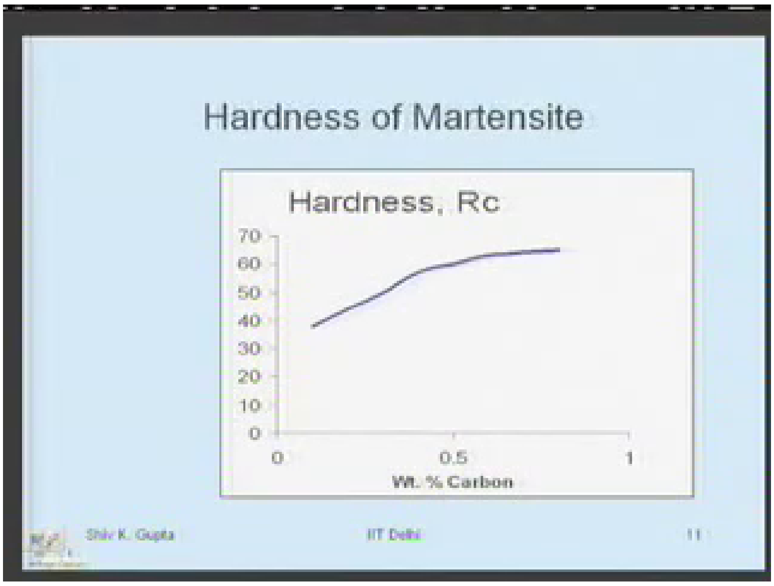

In here I show the hardness of martensite, this is not a very smooth curve I have taken and plotted it, the experimental data. The hardness which is also measure this strength of the material is a functionally carbon contained in the steel; at about 0.6% carbon it reaches probably a high value of about 63 – 65 around somewhere there. That is the hardness you reach at about 0.6% carbon. And less than 0.6% carbon the hardness is decreasing carbon.

At that point steel is very very brittle but here as I lower the amount of carbon hardness decreases and steel may not be very brittle but the hardness is also not very high, strength is not going to be that much so if my intention is to make the steel hard by transforming it to martensite then I must have 0.6% carbon and this is irrespective of what alloy additions are available in the steel, it is a function of carbon, the hardness of martensite is a function of carbon.

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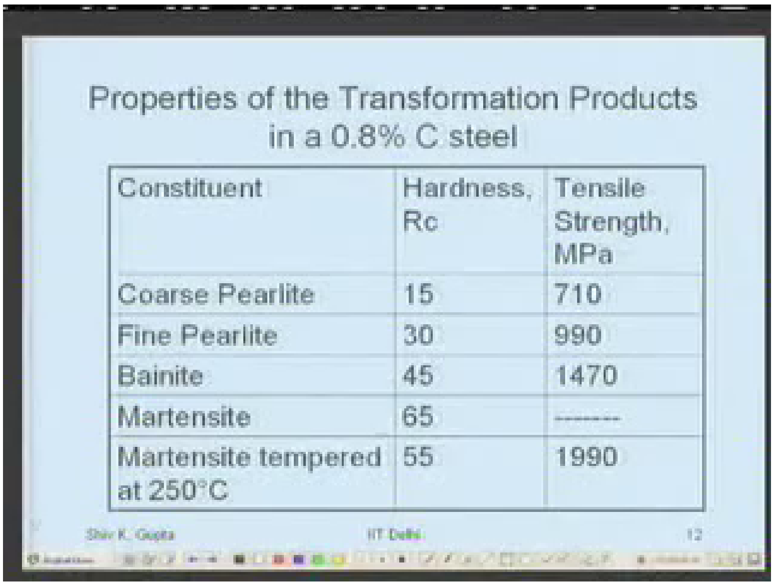
Properties of the Transformation Products in a 0.8% C steel

Constituent	Hardness, Rc	Tensile Strength, MPa
Coarse Pearlite	15	710
Fine Pearlite	30	990
Bainite	45	1470
Martensite	65	--------
Martensite tempered at 250°C	55	1990

In this table I show you the hardness as how it is related to the strength which is the tensile strength we call it. I will explain what the tensile strength and the other (())(19:25) and other things are when I come to the mechanical properties. The tensile strength is related to the hardness that is what I have shown here, as the hardness increases tensile strength also increases.

And the second thing which I am showing here is the coarse pearlite where the distance is between ferrite plate and cementite plate are larger that is thickness of the ferrite plate and that of the cementite plate is large enough. The hardness is small, very soft material but the strength is also less, 710 megaPascal but when it is cooled in air, normalized, fine pearlite, the distance is between thickness of ferrite plate and cementite plate are smaller, hardness is 30 while strength is 990 megaPascal, almost 1000.

When I form bainite, there is still more finer distribution of carbide, its hardness is 45 and tensile strength is 1470 megaPascal, but in martensite it is 65 as I told you for 0.6% and it becomes around there, so at 0.8 it is same value 65, but I am not able to measure the tensile strength because it feels within its elastic limit. It doesn't even yield strength, it is a brittle material.

That is what I want to get rid of, for that temper the martensite, after transforming the steel to martensite by quenching we keep it in elevated temperature, it could be anywhere above room temperature up to about 400 degree centigrade and thereby I try to gain some ductility in the steel so I can measure some tensile strength of the steel and there is some plastic deformation unit but I have to compromise and lose some hardness, 65it goes to 55, that is not the intention.

By tempering I do not want reduce the hardness, that is not my intention, by hardness I want to achieve to make the steel stronger but it became brittle so to gain ductility I do the tempering and I gain the ductility, I get the tensile strength but I lose some hardness, that is a bargain, okay, but that is not the intention of tempering. Let us see what happens during tempering.

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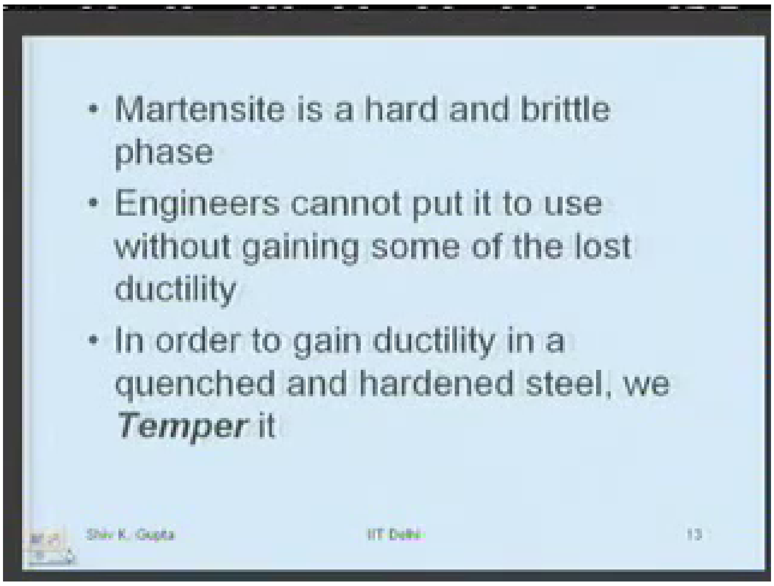

Martensite is very hard and brittle as I already told you and it cannot be put to use without gaining some ductility and in order to gain that ductility as I said we do the tempering of the steel.

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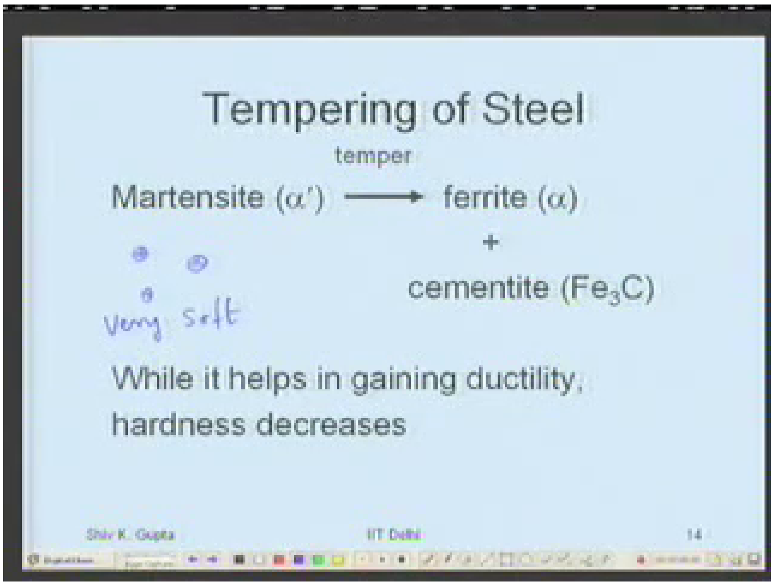

The process of tempering causes a martensite which is a BCT structure when it heat it tempering, I keep it in an elevated temperature, above room temperature usually maybe 200 degree centigrade, 250 degree centigrade but more the temperature you will be losing more hardness. Process would be much much faster because it process in volume diffusion where all the carbon is in solution, martensite alpha said that, it is already in solution, all the carbon.

And this carbon goes to form, diffuse out, becomes ferrite and cementite but the structure which forms now is not pearlite, pearlite is a name given to a morphology where ferrite and cementite plates are (())(23:07) arranged, if you temper the martensite what you will get is spherical carbide or cementite embeded in the matrix of ferrite like this, this morphology of spherical cementite is not called pearlite, similarly bainite is not called pearlite similarly bainite what we call is not like this.

There are plates or laths in between we have the martensite needles inside the plates and in between the laths we have some carbide coming out. So this is what the structure form is altogether different structure, this is not called pearlite, that is the ultimate thing but if that goes to this stage it is very very soft steel. You have lost all hardness It is softer than the coarse pearlite.

Softest variety of steel is this where a cementite is spherical in nature and it is called spheroidized steel. So this is the softest form of steel we have, that is the distribution of cementite in ferrite matrix give rise to very soft whether cementite is spherical shape, gives rise to a very soft steel. But intentional tempering is not to make it soft but to gain some ductility, and as I said hardness decreases is a bargain, I have to compromise on that.

So this process since it is going on at a lower temperature is possible for you to control the time and the extent, therefore the extent of the process if you keep it for a certain time just bring it back to a lower temperature, room temperature where you are going to use it the further tempering will not be there, and you have stopped the process of diffusion of carbon.

Student: So the strength of tempering can be controlled.

Professor: Yes, can be controlled because it is happening at a lower temperature, lower temperature, you are on the lower brand of the TTT diagram and when you are in the lower branch of the TTT diagram the diffusion is slow and it is going to take time, you can control time.

Student: The amount of ductility we want.

Professor: Yes, exactly, you can gain the ductility you want more the hardness you will have to lose, you have to compromise there as already said, so very ductile, very soft but hardness is not there anymore. So we have to stop this process of tempering as we desire, depending upon the hardness I need.

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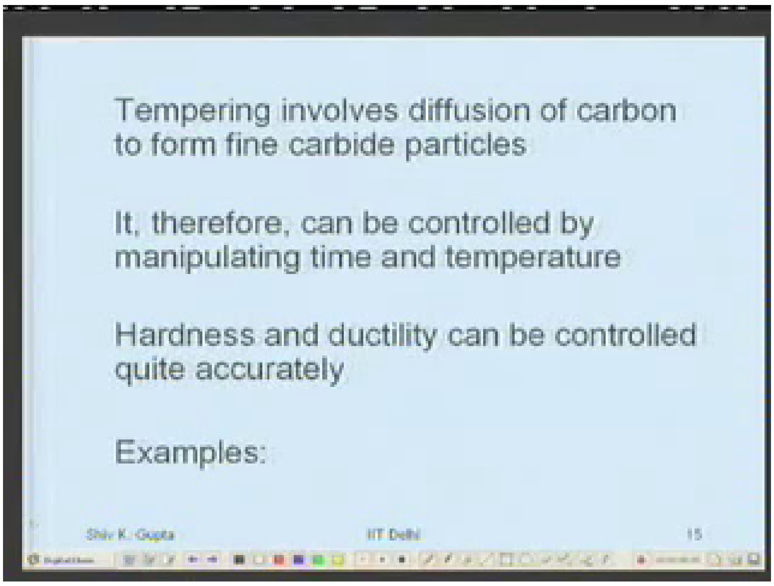

So here now my process involves diffusion of carbon because all the carbon which is in solution in martensite has to come out some in the form of carbide, and by manipulating the time and temperature I can control the extent, to the extent I need it, and it is possible for us to do it very very accurately because the role of temperature is more than that of the time. That is time comes in the logarithmic form but temperature is linear so therefore the role of temperature is much much greater and the control can be made very accurately.

Say for example I was to make a chisel from this steel, I take it to austenite temperature, quench it to make it martensite, but chisel, how the chisel is going to make, hard is needed because I want to cut something with the chisel, I want some hardness, right. So we have hardened it, but now when I use the chisel I have to hammer it, keep it on something so that the edge cuts the object which is softer than this.

When I hammer I apply some impact, brittle material cannot withstand the impact, so my chisel in brittle will not stand, so I need a lot of ductility in it, so I will tamper it to a little high temperature to a greater extent because I need this chisel to be ductile so it can take the impact, right. Same way if I have a hexa blade when I use for cutting, I am not impacting it, it can be very hard, hard edge is required for cutting operation because hard material can only cut the softer material so I need the hardness, I would not temper it to that high extent as I would do it for chisel. Chisel would gain more ductility rather the hexa blade like that we have to control the hardness and ductility in the material.

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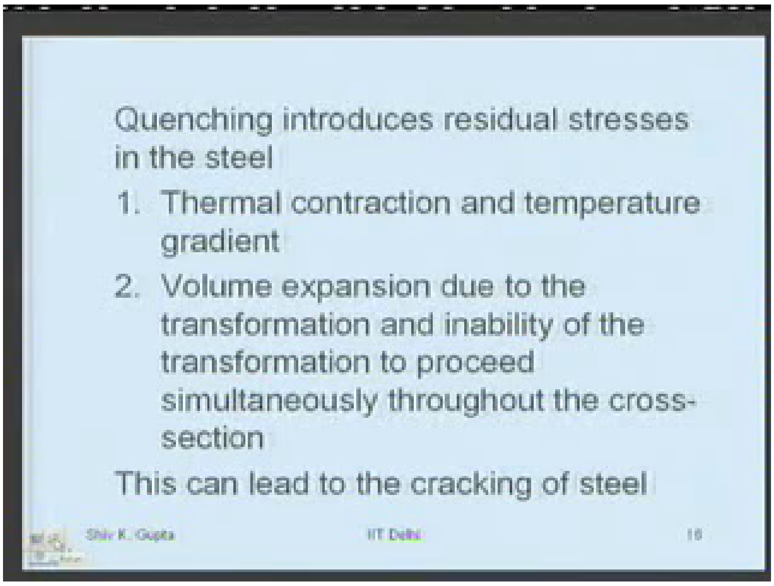

Well that is what I was trying to tell you, quenching introduces residual stresses in the steel, and the reasons I gave you one is the thermal contraction, and second one is the transformation of the matrix which again is not uniform, it is not the whole volume, part of the volume is transforming and that is what residual stresses lead to the cracking of the steel and if you take it in a plain carbon steel, quench it from the austenite temperature invariably it will crack, in water if you quench it. However you may stop this quenching cracking if you can do it in a slower process like dropping it in oil, maybe you can stop cracking.

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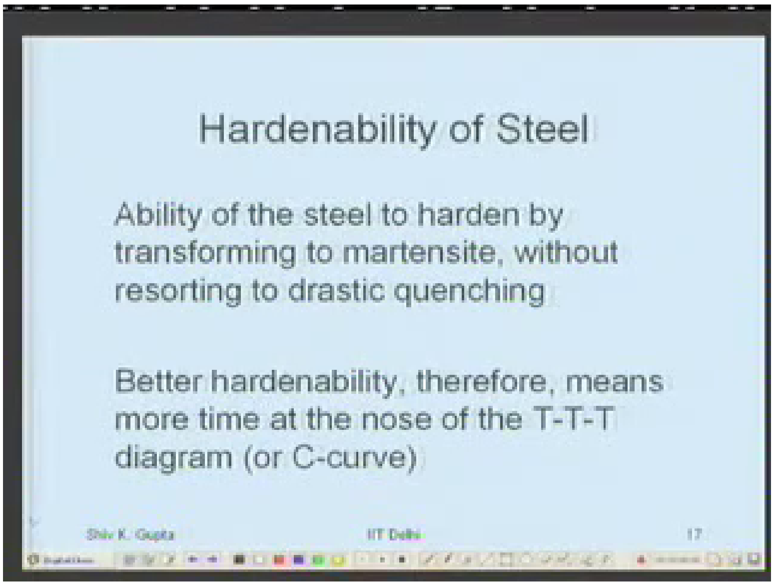

Now how to overcome this problem is very essential for us, it is a very serious problem. For this we would like to make the steel more hardenable. What is the hardenability of a steel. Hardenability is not the hardness of the steel, hardness of the steel, martensite particularly I told you is a function of carbon, if carbon is 0.6% more and it is 65 Rc, if it is less it will be less. So hardness is different from hardenability, hardenablity is the ability of the steel to harden by transforming to martensite without resorting to drastic quenching. What is the meaning of that?

If I do not do the drastic quenching I am doing the slow cooling, obviously little slower cooling so that the surface and the interior there is not large temperature gradient. Heat from the center has come to surface and taken away by the quenching medium, right? The heat has been taken away and the temperature difference between the exterior and the interior is not there. As a matter of fact the ideal situation would be interior and exterior of the steel both of the same temperature. There will be no differential contraction taking place, right?

So therefore for better hardenability we said that there should be no drastic quenching. And then when the temperature in the surface and the interior is same transformation will also take place in the interior as well as in the surface it will form martensite. So I am not only reducing the strains due to the thermal contraction I am also allowing steel to transform interior as well as to the martensite when the temperature is same, right. When the temperature gradient is there surface is becoming martensite interior is not, and that is what I am trying to avoid.

So that is why I said no drastic quenching but it should become martensite and this requires a process of a slower cooling, that for the bay at the nose of the C curve must have high time, once I came it is too small for 0.8% carbon steel, right? For this reason we add some alloying elements to the steel which are subtitutional allowing elements and they give rise to shifting of the nose of the TTT diagram to higher time, higher team means to the right.

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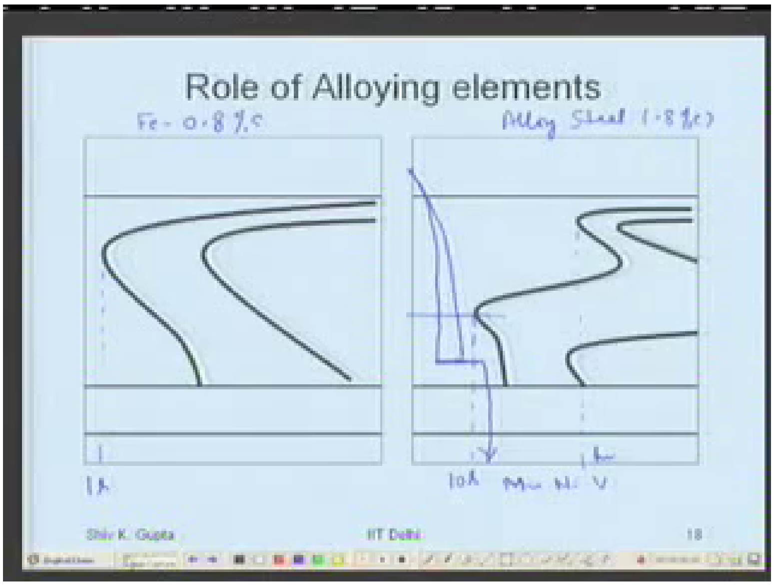

That is what is shown here, this is the 0.8% plain carbon steel and this is the alloy steel 0.8% carbon but it has allowing at divisions like manganese, nickel and vanadium, so on so forth. This time as we already said is about 1 second, here I will show you this time is 10 seconds that is what the bainite knows. The pearlite knows if you look at time would be in the range of R.

Student: (())(33:36) martensidic transformation without having the tension, we have to (()) (33:45).

Professor: Drastic, it should be, see the question is 'Rate of cooling here if it is 140 degrees per second, it should be here less than 50 degrees per second. You have to do the quenching and the rate of cooling has become slower. Another thing when I have so much time available to me I can do is, let us say my surface is cooling like this, interior is cooling like this, okay, if there is enough time for me I can hold it for a while. So the interior and the exterior both are at the same temperature and then I quench it. Then also you can do.

Why did I have enough time here, I am able to cool it such that I do not cross this or do not cross that. I have equilibrated my temperature and then I can quench it. So the exterior and the interior are trying to transform simultaneously, if not happening that surface become martensite interior is still soft austenite, alright. So this is what the alloying additions are doing, they are shifting the nose to the right. By bainite noses at 10 seconds, this is about an hour, an alloy steel. Depending upon what alloying addition I make.

This can go still further, this cannot go that much but all depends on the alloying elements, what alloying elements present. Well there is only one element which is an exception and that is cobalt. If cobalt is added time doesn’t shift to the right, don’t ask me why. That is the only exception, all alloying addition shift the nose to the right so that they buy more time and more hardenability of the steel. So hardenability the way it is define resolves to the fact that I should have more time here at the nose, that is what I am interested in more time so that I can still form martensite and I don’t have to do the very fast cooling, very drastic quenching out, I don’t have to do that. Rate of cooling can be low.

While you can see that if this nose, my guess is about 350 let us say, and this is 725, this temperature is about 400 let us say and I am cooling in 10 seconds, 40 degrees per second is the rate of cooling I require, while I might need about 130 or 135 degrees per second, that is the way the rate of cooling is reduced. Alright. This is one of the functions of the alloying additions made to the steel that they provide better hardenability to the steel by shifting their nose to the right, okay.

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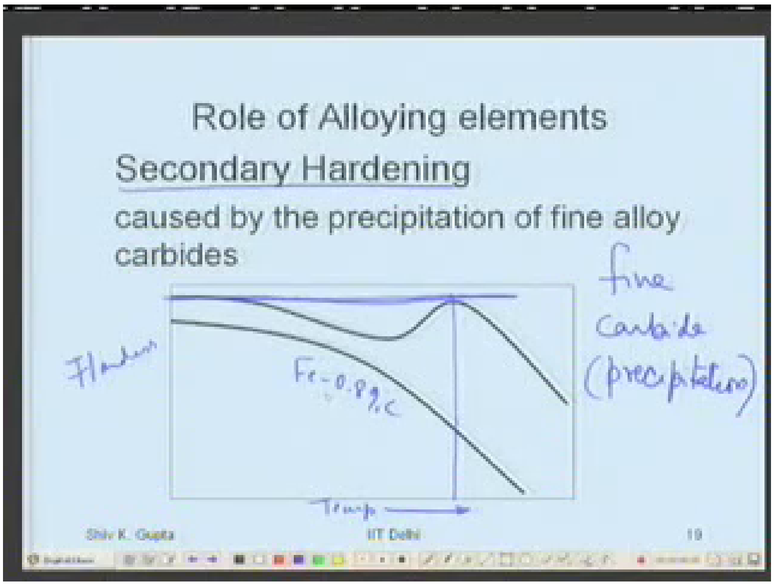

The second function of alloying addition is they refract on the tempering. When the alloying additions are present particularly like chromium, tungsten, and molybdenum etcetera, the secondary hardening takes place in steel during tempering. This is the hardness and here is the temperature of tempering, this is the iron 0.8% carbon steel. Hardness decreases depending upon my temperature, time is as I said is not very effective but let us I have done constantly for all of them for 10 minutes. I will lit here for 10 minutes, I will lit here for 10 minutes and the hardness decreases, decreases very rapidly beyond 400 degrees centigrade.

But when alloying additions are present I get not only decrease due to the tempering process but there is an increase because the formation of very fine carbide which I call precipitation process. Carbide is coming out from the (())(39:00) is a second phase, not always a second phase which comes out gives rise to precipitation. It comes out much faster and then it is not precipitation. When very fine is coming, carbon is diffusing slowly-slowly, carbides are forming and precipitation takes place and that gives rise to increase in hardness.

And as a result you started with this hardness and you have almost the same hardness after tempering, even at 450 degrees centigrade. So you have gained lot of ductility. You have reduced all the stresses but at the same time your hardness has not lost. So alloying additions are doing this also, this subtitutional alloying elements which are present in the steel, I said the steels we have, a thousands of varieties already available, composition and then what treatment do I give it to the rate, and anneal the steel, I normalize the steel or harden the steel, temper the steel.

What all processes I am letting the steel go through my properties of the steel will depend upon, because microstructure is what I am controlling by doing all these things. And it is happening because eutectoid transformation is there cool the austenite to the lower temperature. This secondary hardening which is caused by the precipitation of fine alloy carbide is what we shall look at the next, the process of precipitation itself.

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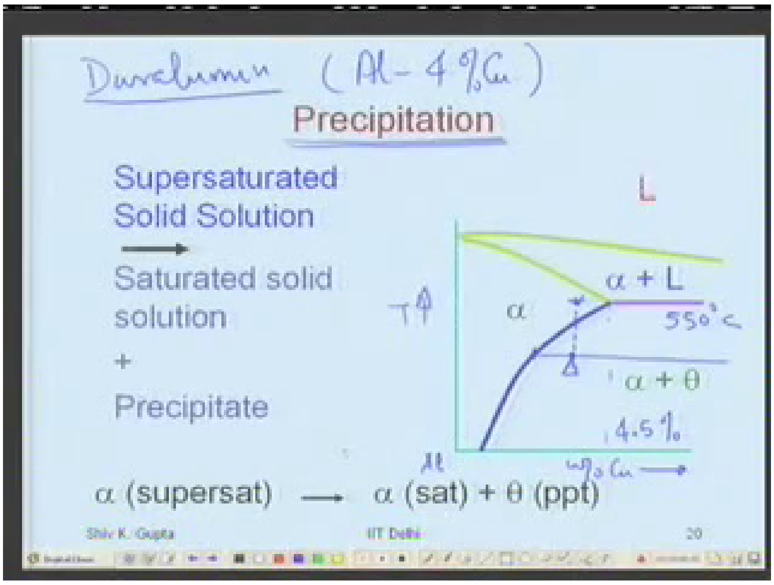

The process I use in alloy which is non-ferrous alloy is in aluminum copper alloy, and this is of course the temperature aluminum copper diagram, part of the diagram I am showing, that is around 4.5%. It is eutectoid reaction, theta phase is about 52 – 54% copper, and the alloy which we use for discussion of the precipitation is duralumin. Duralumin contains aluminum and basically 4% copper, usually there are some additions of titanium like half a percent, we will not worry about that because we are looking at binary diagram.

Let us say I take in alloy with 4% copper and somewhere here, this temperature is around 550 degrees centigrade, it is all alpha here, single phase alpha. If I cool this alloy slowly, when I cross this (())(42:22) line there shall be theta phase begin to form and as I cool more and more, more and more theta phase will form and that will be give by this liver, this is the fulcrum and this is the fraction of the theta phase will be this. If I do slow cooling second phase will form like this.

But what we do is we take it from here when it is all single phase alpha, quench it in water or bring it below room temperature. So I have not allowed any copper atoms to diffuse out of the matrix, everything remains in solution again, right? Now, at room temperature as the time progresses the theta phase will shall began to precipitate out and it forms in the form of small particles. Now, mind it that the super saturate solid solution goes to the saturated solid solution and precipitate that's the ultimate thing which will happen and that is how the precipitation reaction can be written.

When I am talking about this I am working at the TTT diagram, the lower branch of the TTT diagram below the nose of the C curve, I am not working above in the case of austenite going to pearlite we are working in the branch which is above the nose of the C curve at higher temperature, now I am working at a temperature much lower because I already quenched from there to room temperature or subzero temperature, then at room temperature I am allowing the precipitation process to go on.

Now so far I told you that fine grained materials have better mechanical properties, secondly I said if the solute is present it increase the strength of the matrix like in the martensite it is hard, because all the solution is present in the solution. All these things I had to explain when I come to the mechanical behaviour, today I will tell you third thing, that if the inter particle spacing in the precipitate is smaller, higher is the strength of the material, right. If the precipitate which is forming in the martrix or a given volume is solid the large number of particles formed inter-particles spacing would be small.

If only few particles formed they are big in volume each one then they inter-particle spacing would be large, so finer the precipitate I form, smaller will be the distance between the particles and therefore larger will be the strength. This is what you have to understand, I shall explain this how it happens when I come to mechanical properties.

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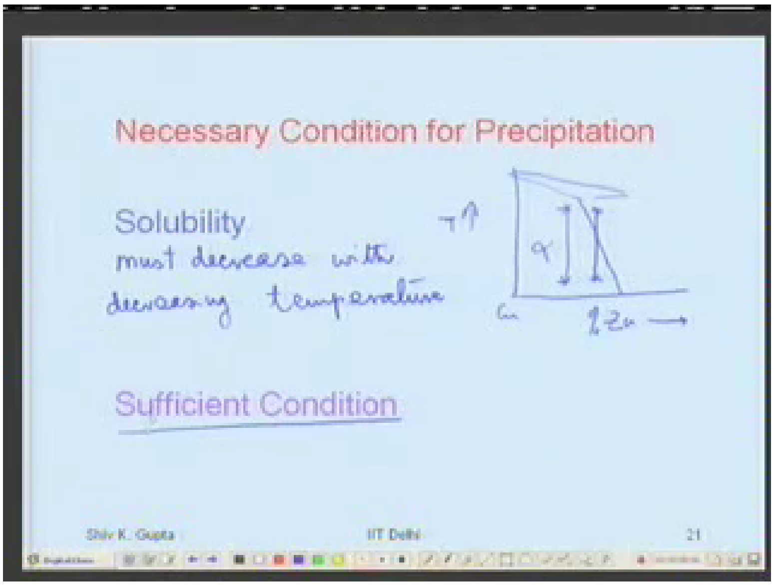

Now for this reaction to take place the necessary condition is to have the reactant. To have the super-saturated solid solution. How can you have the super saturate solid solution, I gave you the example. Aluminum 4 % copper alloy, around 550 you make it uniformly solid solution where it is not even saturated, but when you quench it you make it super saturated because so much of copper cannot remain in solution, at room temperature is only about half a percent copper which is in solution. The rest of it is all making super saturated, right.

So I can get the super saturated solid solution by quenching, provided the solubility decreases with the decreasing temperature, right. When the solubility is not decreasing with decrease in temperature, say for example, copper zinc alloy, this is alpha phase field, I don't make most of diagrams don't worry about that, if I take it here it is a solid solution, I quench it, it is still a solid solution. It has not become super saturated, I am not able to do that, but I take something like here, maybe you can heat it rapidly, here ti becomes super saturated, but how long will it stay.

The higher the temperature faster is the diffusion and do not stay there the super saturated, I want a super saturate solid solution which will stay, should be going towards the saturation in a very-very slow rate then only I get the aging process, the time is large, solubility must decrease with decreasing temperature. The sufficient condition I shall leave out today, after I have explained what causes the aging process of precipitation and giving rise to increase in strength then we shall try to understand what is a sufficient condition. But today only the necessary condition that solubility must decrease with decrease in temperature.

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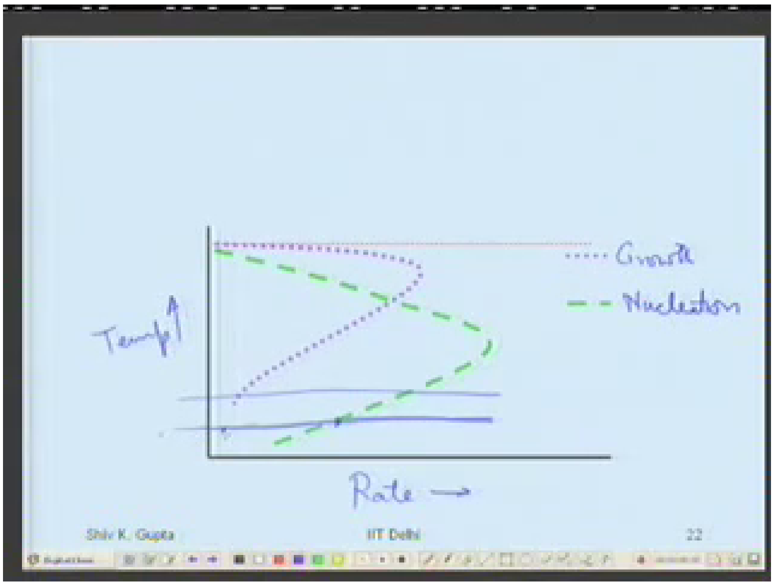

Now this is what I was trying to tell you that these are the rates here, this is temperature, this one is the growth rate and that is the nucleation rate, and that is the equilibrium temperature, that is the temperature of the solvus line, and then quench it to low temperature and we are working in this temperature region. You see as the temperature rises nucleation rate increases but the growth rate is smaller than the nucleation rate and growth rate also increases with increasing temperature but all the time growth rate is smaller than the nucleation rate.

I am not in this branch, I am in this branch. Working at very low nucleation rate, I am working at very low growth rates, and if I increase the temperature both nucleation rate increase, growth rate increase that is what is happening, right? So if I am working at this temperature let us say, some particles nucleate but they are unable to go, but time elapses some more particle will nucleate and slower like that some more particle will nucleate with time, as more and more particle nucleate, right, inter-particle spacing is becoming smaller and smaller and smaller, more particles are forming.

But I cannot fill the whole volume, isn't it. It cannot become 100% because whatever is given by the Lever rule, if it is 5% or 2% or 3% the volume has to become the precipitate, only that much will become, remaining has to remain in the matrix that is what is equilibrium is, it is going towards equilibrium. But the rate of process is so slow and nucleation is so slow rate, I got very fine (())(50:53) but they are unable to grow so I get fine-fine-fin precipitate.

And as the time progresses more and more precipitate I get so more and more, I mean the decrease in the inter-particle spacing is more and more the hardness increases more and more with time. Why this process is also called age hardening, as the time or the alloy, kept at room temperature increases its hardness increases, right?

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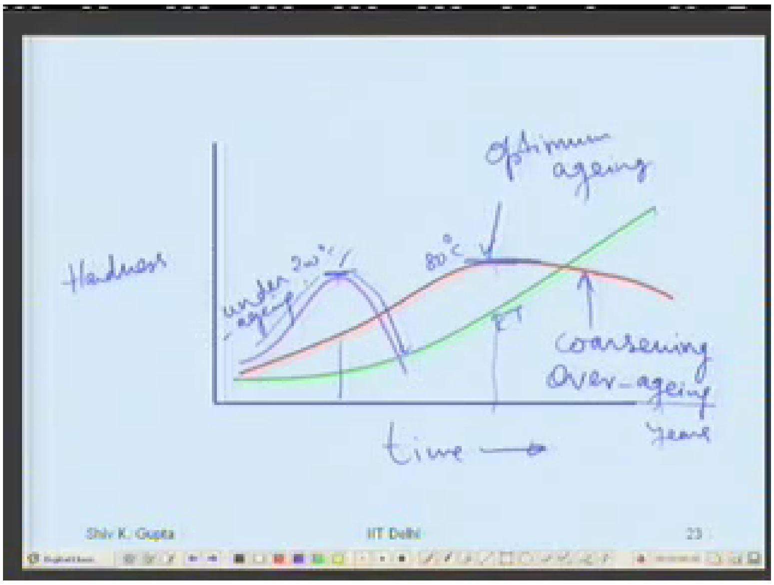

Then this is the hardness and this is the time, usually the logarithm of time scale we use, this is at room temperature, it keeps on and on, maybe this already a few years but at about 80 degrees centigrade it is faster, the maximum is reached in less time less than a year and this is at about 200 degrees centigrade has reached in few hours. What you notice here as I said as the time progresses more and more particles are nucleating, hardness keeps on increasing, inter-particle spacing is decreasing.

But let us look at this one which is passing through the maximum, this will also pass through the maximum but that maybe after 15 years or so. If it passes through a maximum 80 degrees centigrade here why is it passing through the maximum? Whatever volume fraction of the precipitate has to form as given by the Lever rule has formed. No more nucleation would be possible after that. No more particles will be forming, so it reached the maximum.

Beyond that what happens is I have created because of the large number of split particles in large interfacial area and interfacial increase provides the extra energy to the material. Tendency is to decrease that interfacial area that happens when the particles grow in size. So some neighboring particles dissolve and one particle grows, that is what is happening, coarsening of the precipitate occurs here and this is also called over aging. This is called optimum aging.

After optimum aging till the over aging is taking place fraction of volume of the precipitate is not going to change, but here the fraction of volume is changing because total amount of precipitate equilibrium amount has not been formed, keeps on forming. Second thing at higher temperature initial hardness is higher, because in same time more particles nucleate, nucleation rate is higher. Second thing the hardness maximum at the optimum which I get is lower at high temperature, the particles are also growing to the rate of the extent, growth rate is also higher

So lesser particles are able to give me optimum hardening and here more particles are required, here still more particles are required because they are not growing. So if you have understood that we are in the lower branch of the nucleation rate and the growth rate, you will understand this, that is important that is why it is called the process of aging. So the process up to the optimum it is under aging, this is optimum and this is over aging, coarsening taken place there, right?

We shall stop here and talk about something more in the next class.