Materials Science and Engineering
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Lecture – 22
Heat Treatment

Hello friends. So, till now, we have discussed about nucleation in growth during phase transformation and we also discussed now that how we can find out the time required for transformation ok. So, we used two ways to do that, one is through TTT curves and another through CCT curves.

Now, we will go to the actual heat treatments which are used in industry ok. So, we will try to understand different types of heat treatment which are; so you should know the name and what temperatures they do those temperature those heat treatment ok. So, this is more like just in lot of information, technological information important for engineering practice engineer, practising engineer ok.

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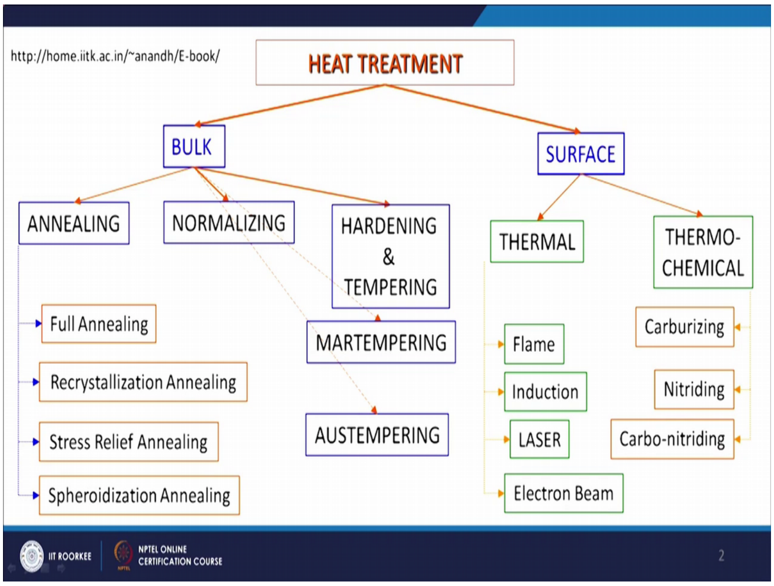

So, today's lecture will be on heat treatment. This is a overall one snapshot of heat treatment ok. I took it from this particular E-book, a very good book you can also refer this E_book from Anand Subramanyam in IIT, Kanpur ok. So, heat treatment can be divided into bulk heat treatment or surface heat treatments.

In bulk heat treatment you can have anything normalizing, hardening and tempering, martempering, austemerping all this heat treatment we will see. In annealing also it can be full annealing recrystallization, annealing stress relieving, annealing or spheroidization annealing. And for such surface treatment you can have thermal surface treatment or thermo chemical. In thermal it is only the flame through flame you do take flame and do treatment and because as you can see now, from after understating understanding the TTT and CCT curves. Suppose I heat the surface by any means which is able to heat only the surface let us say may be up to 1 mm or 2 mm depth suppose you have induction heating or laser heating or electron beam heating with where they have very concentrated source and the heating will be very localized. And then you stop the heating.

What will happen? The whole bulk of the material is still not heated up, it is still maybe at room temperature or let us say slightly higher temperature ok, but the surface is a went into let us say in the austenite phase by heating. So, now, the surfaces get so much material which is not heated up and so it will cool very rapidly. So, you can have localized transformation where you can get a different type of phase let us say martensite phase ok, and martensite phase is a very hard phase it has a very high hardness ok.

So, by doing this the type of thermal treatment I can have a very hard surface and still my bulk of the material is soft. Thermo chemical if you see already we have discussed about diffusion. So, you can have carburizing where carbon can you can diffuse and you can understand that by changing the chemistry I can change lot of things. I can change the microstructure locally I will have more of pearlite. So, may be better properties become better mechanical properties on the surface. You can do nitriding similar to carburizing where now, nitrogen is diffused inside the surface or you can have carbo nitriding ok.

So, there is a plethora of heat treatment processes ok. Right now, we are concentrating on the bulk heat treatment. Before going further let us see that what are the temperatures which are important in the iron carbon phase diagram ok.

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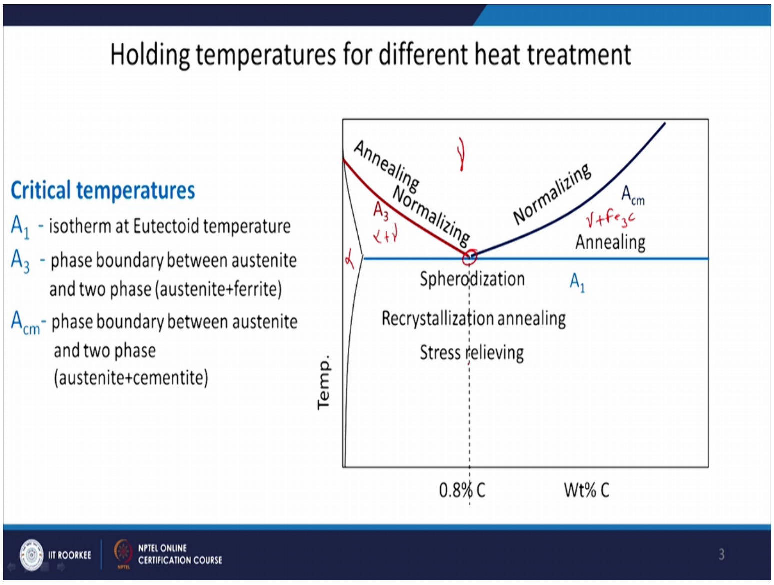

And we are only concentrating in mostly this part where the steel is going to be there and also only in the part where you have where you are going to have a solid state phase transformation. So, you have austenite here ok, I have austenite here ok, and you have alpha ferrite here and on the other side you will be having cementite and this is where you will have eutectoid reaction. So, there are two three temperature critical temperatures shown here one is this a three line where my alpha plus gamma transformed to gamma. You have A cm line where your gamma plus Fe 3 c transform to gamma and you have A 1 line which is related to eutectoid temperature.

So, there are a couple of important critical temperatures here and you can see as a composition of my alloy is going to change the temperature this A 3 temperature is going to change that is obvious. So, these are critical temperature A 1 is the isotherm at eutectoid temperature ok. A 3 is your phase boundary between the austenite and two phase austenite plus ferrite, A cm is the phase boundary between austenite and two phase austenite plus cementite.

So basically on this we have now, also plotted that at what temperatures you are going to do a particular operation. For example, where you are going to do annealing, where you are going to do normalizing ok, if I want to do normalizing I will have to go to a temperature above A 3, similarly for annealing this is for a hyper eutectoid steel normalizing will be above A cm, but annealing will be above A 1 temperature. Then the spherodization where you are going to do recrystallization annealing or stress relieving where you are going to do ok, all those temperatures are marked here.

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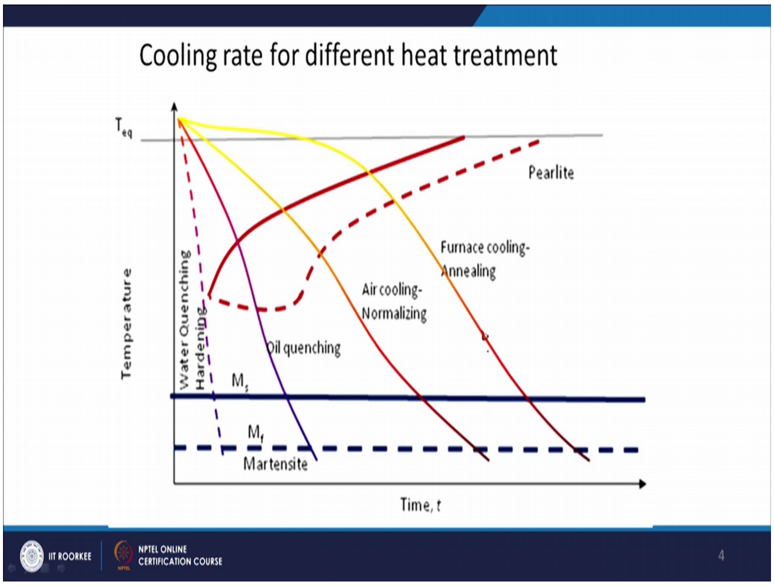

So, now, what are the these are the holding temperatures for different heat treatments. And what will be the cooling rate for different heat treatments ok? You can see that I can have furnace cooling. So, very slow cooling rate ok. This is this will give you furnace cooling which is what we do in annealing. This is a faster cooling rate means I have taken the product out of the furnace and I am doing air cooling.

So, furnace cooling means I take the furnace to that temperature keep it at the temperature for some time. So, that my whole product is homogeneously heated to that temperature and then I a switch off the furnace ok. So, now, furnace is going to cool, my product is going to cool. So, it is a very slow cooling process and that is what we will have in furnace cooling and that is what we follow in annealing process.

Then we I can take the product out from the furnace. So, in air it will get cool. So, through convection currents and then of course, it will be higher cooling rate than furnace cooling and that is what we do in normalizing. You can do oil quenching you take it out put it in the oil of course, now, oil quenching will be much faster than air cooling ok. So, you can have a faster cooling and these all cooling curves are superimposed on a CCT curve as shown here you can see that. So, now, you can also understand that if you are doing furnace cooling what microstructure you will get if you are doing for air cooling what microstructure I am going to get. If I am doing oil quenching what microstructure I am going to get, and if I am doing a water quenching which type of microstructure I am going to get.

For example, if you take oil quenching here my cooling curve has crossed the pearlite start temperature ok, but it has not crossed the pearlite end temperature or end curve ok. So, the transformation is not completed here and now, it is crossing the ms temperature. So, what it will happen in this case, that some austenite will transform into pearlite and the remaining austenite will transform into martensite, ok. So, it will not be a complete transformation into one phase some portion will be martensitically transformed some portion will be transformed into perlite and like that.

For air cooling and furnace cooling you can see that it has crossed the start temperature and end temperature. So, in this case the transformation is complete here whereas, in this case it is not. Or I can do water quenching also in that case I will be skipping this nose this. So, there is no diffusional transformation and the cooling is fast enough to cross to directly go to the martensitic temperature where martensite start is there. So, now, in this case I will get the martensite directly ok.

So, now, we will come to individually one by one try to discuss each heat treatment. First one is annealing, either you can say full annealing or you can just say annealing.

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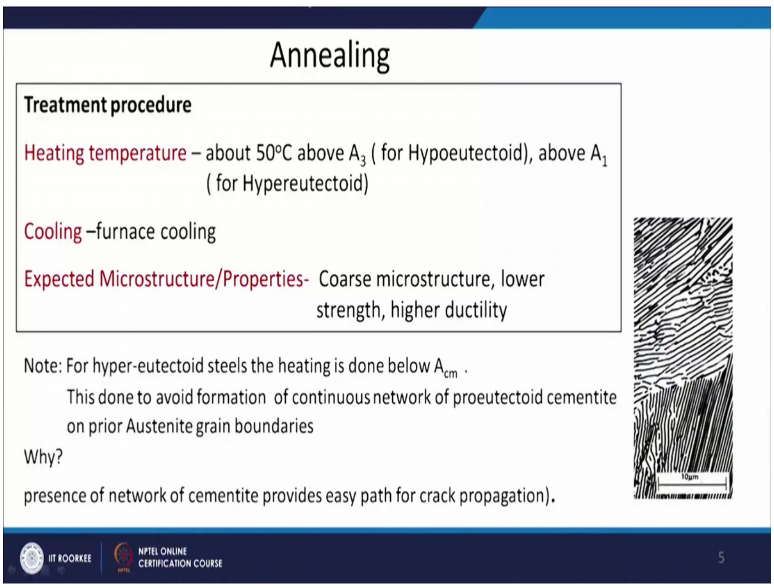

What is the treatment procedure? Heating temperature is above about 50 degree Celsius above a three temperature. So, A 3 temperature is there you just go 50 degree Celsius above that and there you hold it. So, if you want to have for hypo eutectoid still it is 50 degree Celsius above A 3, and for hyper eutectoid it is 50 degree Celsius above A 1 temperature. So, in this case we are not crossing the A cm temperature ok.

And then cooling will be done by furnace cooling what is the expected microstructure and properties you will get course microstructure because I am doing this very slow cooling here. And of course, because I am getting coarse microstructure this is you will understand when we will discuss mechanical properties that it will have it is going to be, going to have low strength and it will have higher ductility.

Note is there for hyper eutectoid steel the heating is done below A cm temperature, this is done to avoid formation of continuous network of proeutectoid cementite on prior austenite grain boundaries. If you remember when we were showing you proeutectoid ferrite ok, they were proeutectoid ferrite was forming on the grain boundaries the austenite grain boundaries and because of that it is it was getting a continuous network of cementite.

Now, please understand that cementite is a hard face and a brittle face. So, if any crack in nucleates it is easy to go along this boundary and your material will fail without any warning actually. So, this presence of network of cementite provide easy path for crack propagation. So, now, we have not discussed about this all the crack propagation and what do we mean by that. But right now, you take it from us that from me that this type of microstructure is not good for mechanical properties ok. I do not want a continuous network of cementite forming that is why I for annealing I am going to do at a temperature A 1 at a temperature above A 1 not A cm, ok.

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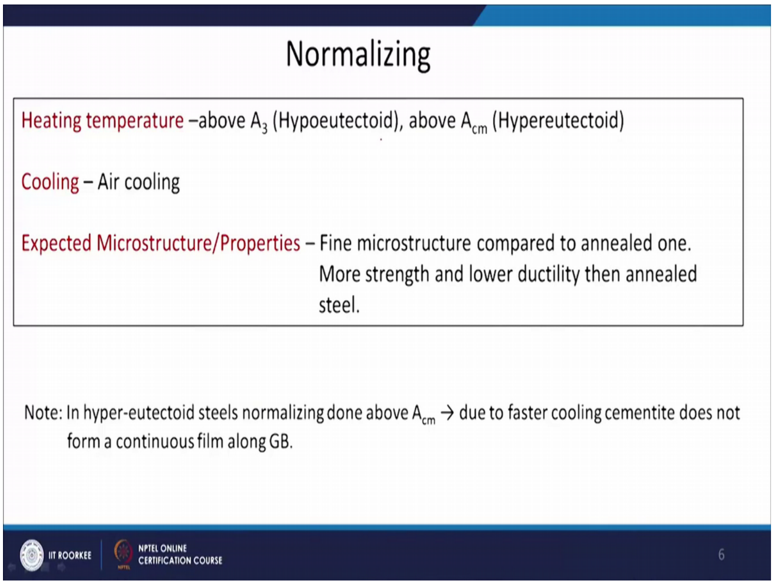

Normalizing, heating temperature above A 3 as we discussed for hypoeutectoid and above A cm for hyper eutectoid. So, in this case I am going above A 1 ok. Why I will be able to do that? Because I am doing a air cooling ok. So, in this case your chances of getting those continuous network of cementite is not there. Expected micro structure properties fine microstructure compared to annealed one because we are doing faster cooling, more strength because of that and lower ductility then annealed steel in hypereutectoid state normalizing then above A cm due to faster cooling cementite does not form a continuous film along the grain boundaries ok. So, here I can do go above A cm.

Then when you have this cementite in this network form or when you have cementite in pearlite also when you have cementite in this elongated lamellar form ok, this is not a very good microstructure ok. So, for that to take care of this long cementite layers ok, what we do is what we call is spherodization annealing; that means, I want to make cementite instead of this long, long lamellas I want to make it as spherical cementite and that is why it why it is called a spheroidization.

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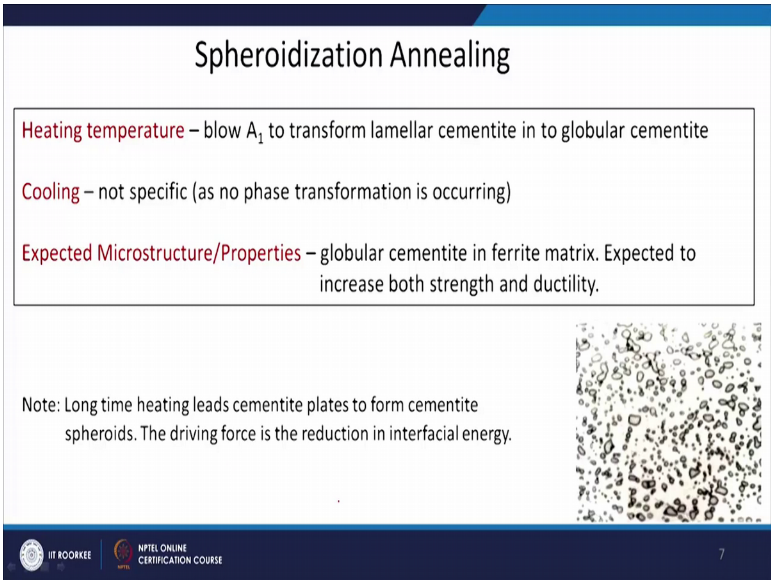

So, heating temperature. Again what will be the heating temperature? It will be below A 1 ok, to transform lamellar cementite in to globular cementite. So, you have will have globules of cementite. Cooling, not specific as no phase transformation is occurring in this case cooling is not important because we are not crossing the austenite boundary here ok. If you remember I will just show you very quickly.

This was the spherodization temperature we did not cross the a one temperature. So, there is no phase transformation which has started. So, cooling rates are important only when you are having any phase transformation ok. In this case because we have not crossed the austenite we are just doing a annealing at a temperature below A 1, so cooling is not very important here ok.

So, in this case no specific cooling rate you can have faster you can have slower of course, if your product is big I cannot have fast cooling otherwise there will be thermal stresses in the material. So, cooling can be decided depending upon the size of the product. What are the expected microstructure? You will have globular cemented that is why we are doing this annealing, in ferrite matrix expected to increase both the strength and ductility. So, you will instead of those long cementite ok, you will get spherical cementite like this. Why you get this spherical shapes? Long time heating leads cementite plates to form cementite ferrites the driving force is the reduction in interfacial energy ok.

So, for the same volume of let us say per cementite if I have this kind of elongated morphology you will see that the surface area is maximum is going to be large here and for a for a given volume the smallest surface area is always going to be there for a spherical shape. This already we know from geometry that for any given volume if you have a spherical shape that is going to have the minimum surface area that is why we do this spherodization.

You can have another operation called stress relief annealing again some of these ideas are you will be able to understand more clearly when we will go to mechanical properties. Then you do any deformation plastic deformation you introduce stresses in the material and in some cases these stresses are not good for service application ok. So, we have to do a relieving of stress relieving operation and to do that. So, to relieve stresses developed during cold working during any forming or any let us say rolling operation or extrusion operation. So you any cold working machining or welding processes ok, you whatever stresses you are going to develop that can be relieved by doing a stress relief annealing.

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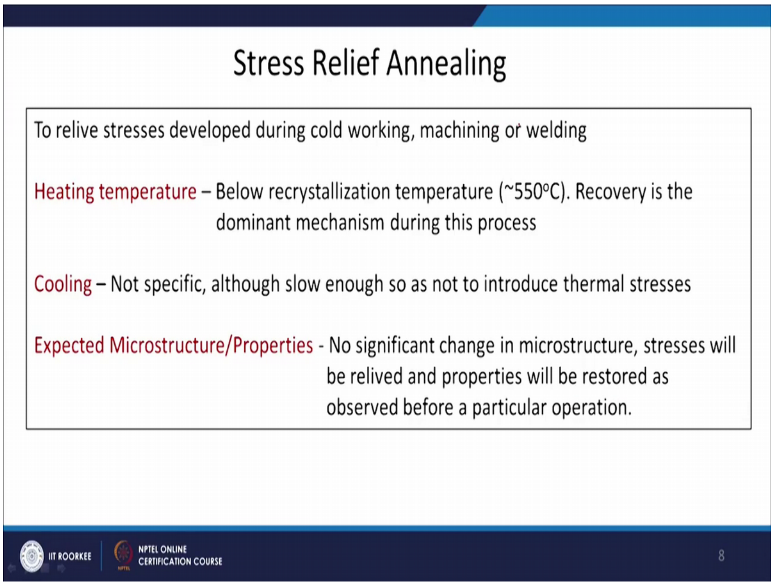

So, it is done below recrystallization temperature at around 550 degree Celsius for plain carbon steel. Recovery is the dominant mechanism doing this process. So, this recovery also we will see when we will discuss mechanical properties.

Cooling again not a specific because we are not doing any phase transformation, although it should be slow enough not to introduce any thermal stresses. As you can see in welding also the stresses are developed because you have thermal stresses you go to very high temperature where the welding is taking place ok. So, you develop thermal stresses in the material. So, when we are cooling it, we should not introduce again the same thermal stresses.

There will not be any significant change in microstructure, stresses will be relieved and properties will be restored as observed before particular operation. So, whatever properties were there before any of this operation cold working machining or welding that will be restored by doing this stress relieving ok. Then there is another process called recrystallization again you will be able to understand more clearly when we go to mechanical properties ok.

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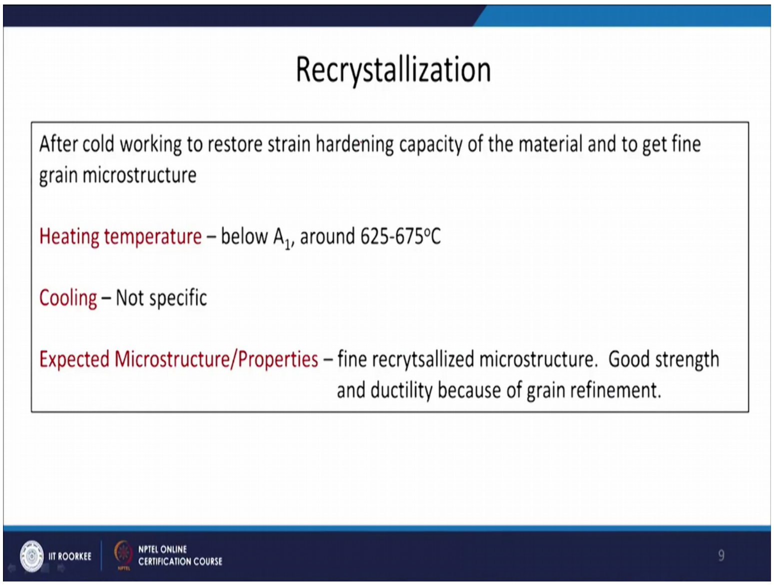

After cold working to restore strain hardening capacity of the material and to get fine grain microstructure this recrystallization treatment is given. Heating temperature is below a one around 625 to 675 degree Celsius for plain carbon steel.

Extracted microstructure fine recrystallized microstructure good strength and ductility because of grain refinement. So, all these things we will see when we will discuss mechanical properties that what why we get very good ductility when you good strength when we have grain refinement. In this particular term also you will understand when we will discuss the mechanical property strain hardening capacity of the material and to get fine grained microstructure ok. This is another type of heat treatment given to materials.

Then there is another heat treatment procedure called hardening ok, and this is to impart high hardness to steel by producing martensite in steel. So, martensite is a very hard phase ok, very hard, very high strength very hard ok.

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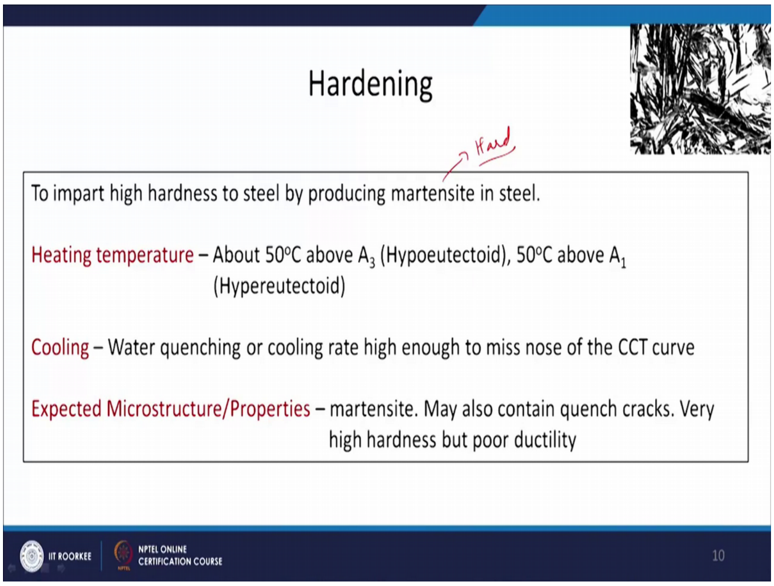

So, if I want to have hardness or in the material I will do a heat treatment give a heat treatment called hardening. So, this is a microstructure of a similar of a martensite ok, you can see all these martensite plates are there this martensite plates are there and zig zag arrangement. So, heating temperature is about 50 degrees Celsius above A 3 for hypo eutectoid and 50 degree Celsius above A 1 by 4 hyper eutectoid. Cooling is water quenching or cooling rate high enough to miss the nose of the CCT curve ok. So, coding has to be high enough. So, that I do not have across the c the nose of the CCT curve.

When you do water quenching if your product is big you can understand that there will be lot of thermal stresses in the material ok. So, it is always advisable to add alloying elements if you want to do hardening. So, that the nose of the curve shifts towards the right and you get enough time to or you can have a slower cooling rate also to get martensite ok. Basically this was not explicitly told to you when we were discussing TTT curve ok. So, let me just explain this idea to you that, suppose this is your let us say we are discussing TTT curve here and this is my martensite start temperature.

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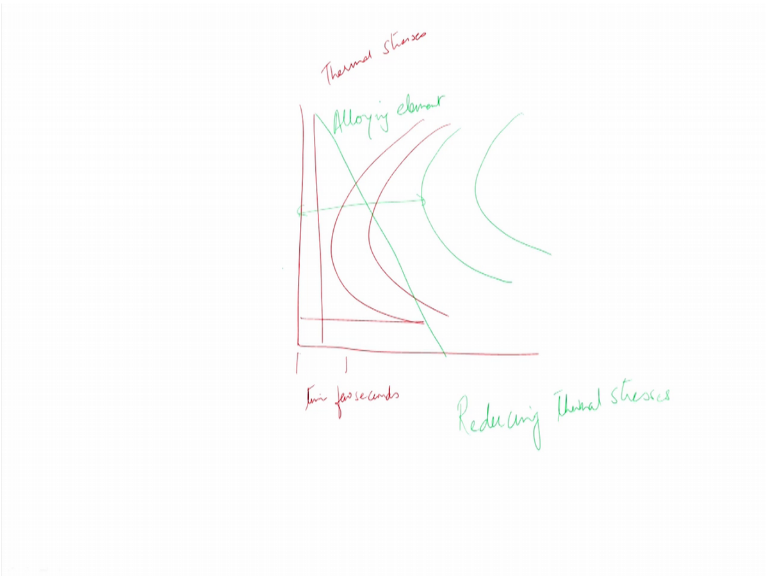

So, usually for plain carbon steel this knows the time which is required to miss the nose is around here it is in few seconds basically. So, I have to have very high cooling rate. So, that I miss this nose ok.

Now, when you have very high cooling rate you are going bound to introduce lot of thermal stresses ok. Now, you this also we have understood now, that all these kinetics is because of diffusion process austenite transformed into pearlite austenite transformed into ferrite and so on ok. So, if by any means I can reduce the diffusion process or if I can make the diffusion slow a slow process I can shift the nose towards the right ok.

So, by adding alloying element let me plot a new TTT curve in a different color, suppose I add alloying element, so now, when you have transformation from austenite to any other phase there has to be redistribution of this alloying element in austenite they may have different solubility in ferrite they may have different solubility. So, they have to this alloying element also have to redistribute between austenite and ferrite ok.

So, what will what will happen because of that when I add alloying element? My this curve shifts towards the right. So, it will go somewhere like this ok. So, now, I am going to give enough time for having a martensitic transformation. So, now, I can have much slower cooling and still I will be able to get martensite because I am able to skip the nose by doing that I am reducing the thermal stresses, ok. So, that is the idea of adding alloying elements in steel. If you have plain carbon steel you have to have on the water quenching to get martensite ok. So, that is what we are saying water quenching or cooling rate high enough to miss nose of the CCT curve, I can shift the nose of the CCT curve by adding alloying elements and let us say then I can do a martensitic transformation by oil quenching also which is a much less severe process ok.

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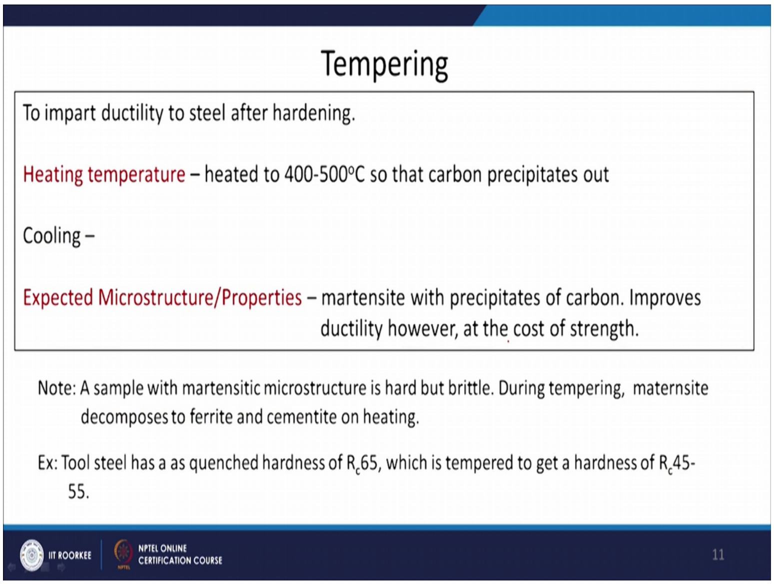

Now, since martensite is a very hard and brittle phase ok. We have not come across these terms till now, ok, but take it from me that martensite is a very hard and brittle phase ok. So, what happens is that when if you have a martensitic steel in a plain carbon steel suppose you have martensitic phase you cannot use it in the any application because if you have any small impact also it will fracture.

So, to impart any ductility to steel after hardening what we do is we do a heating at around 400 to 500 degree Celsius. So, that carbon precipitate out. So, when you as I told you if you remember martensite is a metastable phase ok. So, if I take it to a little bit again higher temperature what will happen is it will dissociate into two stable phases which is ferrite and cementite.

So, if I do a little bit heating what will happen the carbon which is trapped in the martensite during diffusion less transformation that will be able to come out in form of cementite ok. So, that is what is we are saying here.

The expected microstructures microstructure is martensite with precipitates of carbon improves ductility; however, at the cost of strength. The strength of this martensite the tempered martensite will be lower than the hardened martensite and, but it will have better ductility. Some nodes are there a sample with martensitic microstructure is hard but brittle, during tempering martensite decomposes to ferrite and cementite on heating decomposes to ferrite and cementite on heating. Tool is still has a as quench hardness of around 65. So, this we will see what do we mean by these hardness values which is tempered to get hardness of around R c 45 or 55 ok.

2D steels are the steels where you do some allowing in the steel and this can be easily hardened by oil quenching ok, and that is what you use in industry for making dyes and so on. Then there are a couple of very interesting processes one is for example, mar tempering it is to reduce the thermal stresses in hardened steel.

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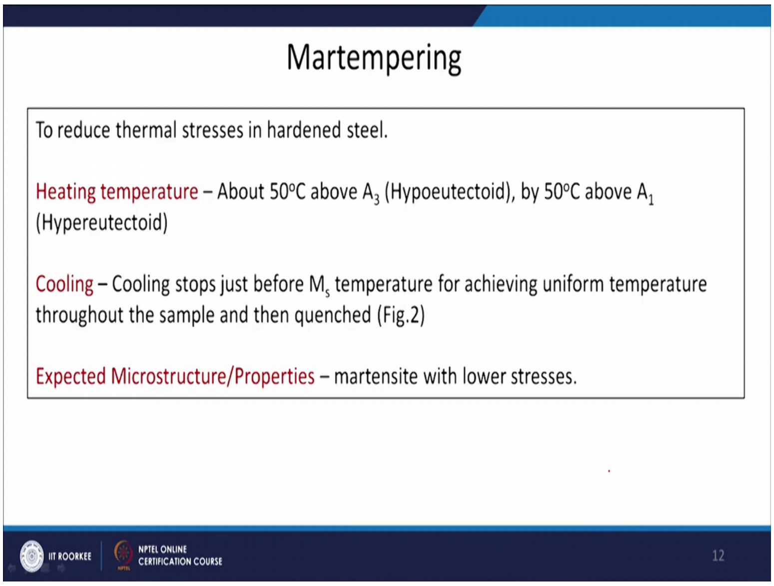

So, you can have water quenching also ok, but to reduce thermal stresses we can do a little bit we can be smart enough here a trick we can use a trick here and that is what we do in martempering that to reduce the thermal stresses I use a process called martempering I will show what do we mean by that.

So, heating temperature is about 50 degree Celsius above A 3 for hypo eutectoid and 50 degree Celsius above A 1 for hyper eutectoid. Cooling is stops just before the ms temperature ok. So, you can have very high cooling rate, but you stop at a certain temperature above ms temperature for achieving uniform temperature throughout the sample and then it is quenched. Expected micro structure properties martensite with lower stresses will be formed ok. Sometime when you do this kind of very fast cooling what happens is martensite itself is hard and brittle and at the top of that you also have this thermal stresses which can introduce some cracks in the material even before any stresses are applied that we do not want. So, we can reduce the thermal stresses by doing a mar tempering operation.

There is another very interesting pro heat treatment called austempering ok. What we do in this is to ganite, get bainite by isothermal transformation.

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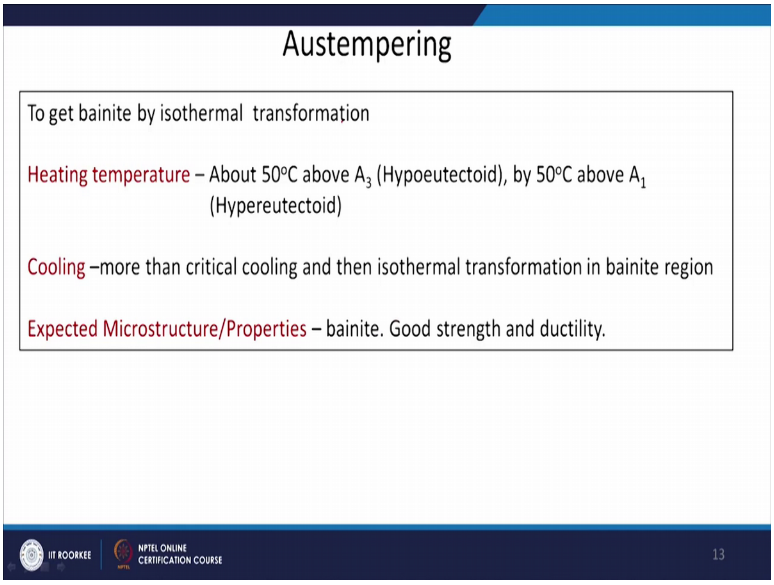

Now, if you remember I said that you cannot get bainite in normal coolings, in if you are doing continuous cooling. So, bainite can be of course, can be you can get by isothermal transformation. So, heating temperature is again same as we did in martempering. Cooling more than critical cooling and then isothermal transformation in bainite region. Expected microstructure bainite good strength and ductility.

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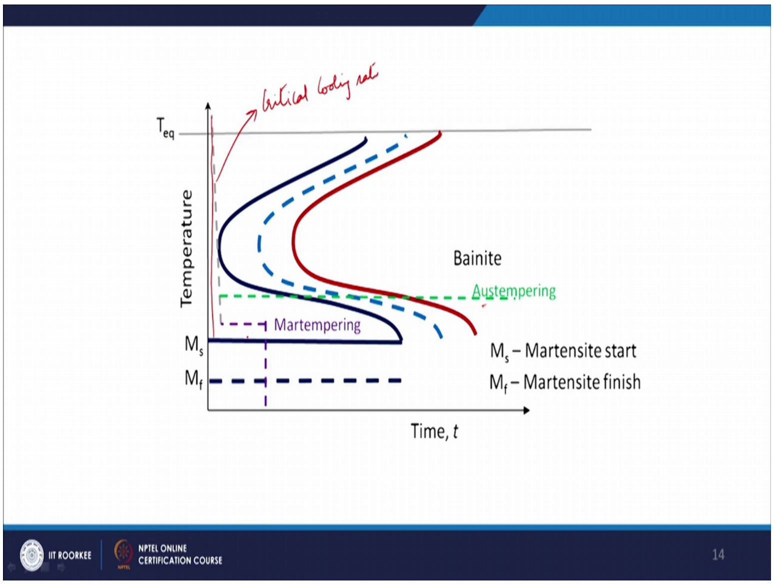

So, this is what these two treatments are called. So, more tempting you do very fast quenching and just avoiding the nose where the diffusional transformation can takes place ok. And then we are holding just above the martensitic start temperature to have equalized temperature throughout the sample. So, this will by this we are trying to reduce the thermal stresses in the material ok.

We are giving enough time for temperature to stabilize and have a uniform temperature throughout the product, and then you are doing the quenching to get the martensite. Similarly I can do for austempering that I skip the nose, we have cooling up to this point and then I am holding isothermal holding to get bainite. So, this is what we call as a austempering ok. And you can see that just skipping the nose ok, so they I can define a cooling rate which is just skipping the noses critical cooling rate. So, if any cooling rate which is more than this is bound to skip the nose here. So, this is cooling rate which is critical cooling rate which is just missing the nose.

So, when you have a certain TTT diagram ok, if I say the cooling rate should be more than the critical cooling rate; that means, it is more than a cooling rate which is just skipping the nose ok. Just to be safe that there should not be any diffusional transformation during the cooling ok. So, this is martempering is a very smart process you can see that I am holding it to avoid the thermal distresses ok.

So, these are the different heat treatments. There are in fact, even more heat treatments possible with materials ok, one has to be smart enough to devise those heat treatment and this basic ideas only give you new ways to devise these new heat treatments ok, and it will not be an end of heat treatment research. People will keep coming with new heat treatment depending upon their understanding of the microstructure the kinetics the thermodynamics and so on ok.

So, with that thank you.