Principles of Physical Metallurgy

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Lecture No. #35

Heat Treatment of Steel (contd.)

Good morning. We continue our lecture on heat treatment of steel; this is the fifth lecture on this topic, and if we try and recall what we have done so far.

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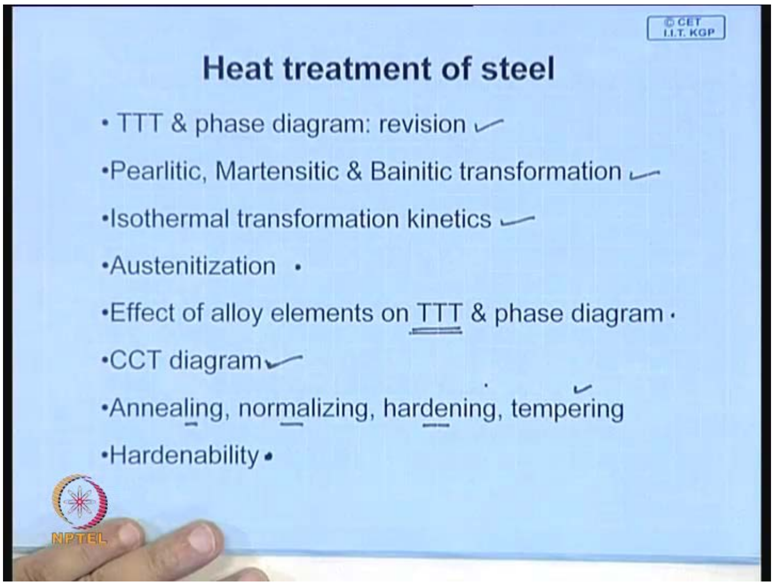

We will find that these are the things which have been covered, this we have covered we have covered this. We also have looked at isothermal transformation kinetics detail. Now these are the things, which are left we have not covered here. Let us see we will try to cover this, we will try to cover effect of alloy elements on time temperature transformation diagram and phase diagram. We have looked at continuous cooling diagram and seen that why it is necessary, I mean TTT diagram is a isothermal diagram, and it cannot be use to predict the micro structure in material, which you get in all conventional heat treatment, where you use continuous cooling; so like annealing, normalizing, hardening.

Here where the main transformation takes place it is a function of cooling rate and the material or the job is cooled continuously. We have also looked at tempering we are looked at why after hardening this comes after hardening and why after hardening it is necessary to temper and this is the topic which is still left is harden ability. So, today we will concentrate primarily on these three this and a few points before we begin, if you can look back these three common heat treatment proceed here annealing, normalizing and hardening.

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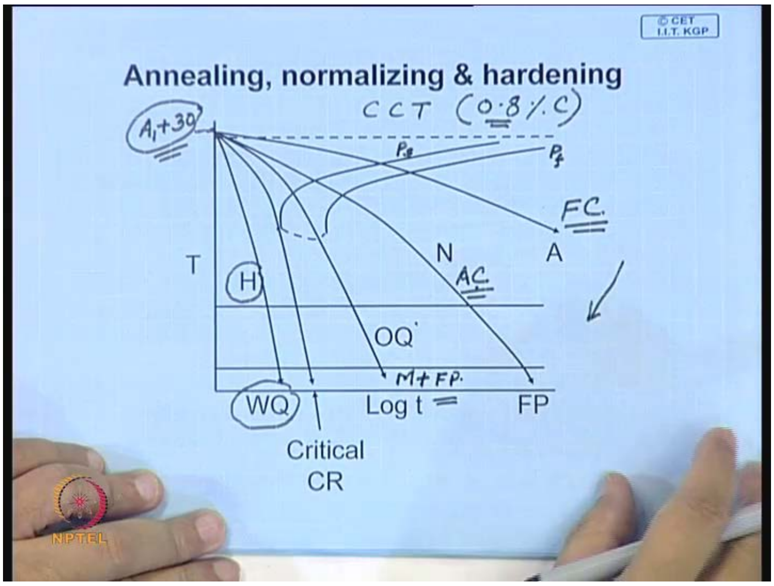

If you super impose the cooling curve on the continuous cooling diagram that we have drawn here is a CCT diagram and this is for 0.8 percent carbon steel with where you which is a more specifically eutectoid steel. Now in this, but you do you heat the job to a temperature where it transforms in to austenite. So, this is the temperature which is A 1 plus around 30 degree to 40 degree centigrade and you soak it a sufficient length of time to ensure that entire steel has been converted into austenite and after that if you are annealing you cool in a which is a very slow cooling you cool in furnace, which is a very slow cooling whereas, in normalizing you take out the job let it cool in year. So, air cool whereas, to harden you water quench and when you water quench the cooling rate is very fast.

So, that means to get a harden structure you have to ensure that your cooling rate is faster than this particular rate. We just avoid this the fusion control transformation so, these are the line, this is the pilot transformation start line, this is the pilot the composition formation of pilot is complete any early completed of along at this profile gives you the time at which pilotic transformation is complete and we have mention time and again by isothermal by continuous cooling diagram in plane carbon steel we do not get (( )). Now if you quench adopt another methods of crunching, say suppose you oil quench in that case so, may be this is the cooling curve somewhere here and possibly and mind we will come later what this term means the rate at which you will be able to cool a job.

But never the less what is important to get harden structure your cooling rate must be greater than the critical cooling rate, say suppose water crunching and may be that if you quench in while you may not be able to attain that kind of a cooling rate then you get a mix structure which will be martensite plus (( )) and as you go this way you will find the structure becomes final and strength goes on increasing. Now since we talked about this rate of cooling is quite important and the rate of cooling will obviously depend on the size of the job, if your job is large even if you quench in water.

So, may be the surface will cool very fast, but the center may not follow the same rate of cooling. So, what means is during the process of cooling you will have a thermal gradient and this magnitude of this thermal gradient will be a function of the rate at which you are able to extract heat and also it will depend on conductivity of the material which we can say if we say that this is same, I mean this does not change much with the composition. Then primarily it will be the dimension of the job that will control the temperature difference between the surface and core at any time.

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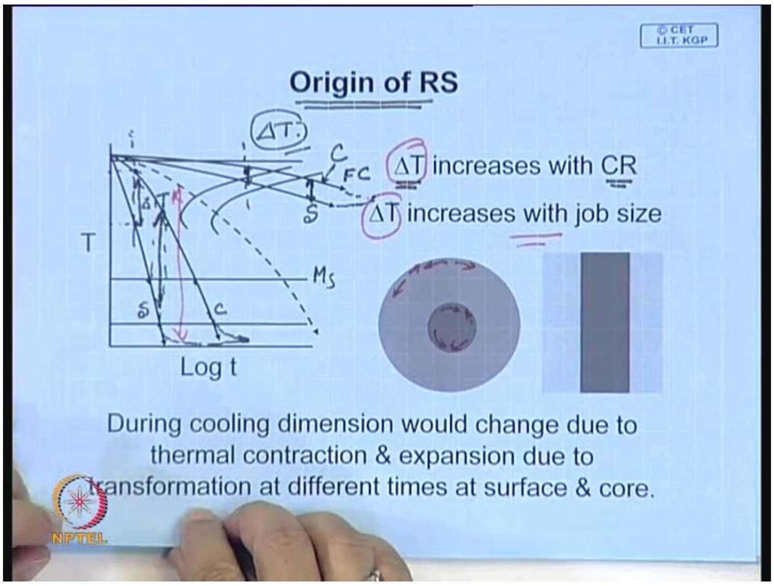

Let us look at the little more detail and then you will appreciate why which was mention earlier say origin of residual stresses and say suppose you are cooling in (( )). So, in that case your cooling in furnace where you expect so, this is a job and the dimension of the job will determine the rate of cooling at this surface cooling rate will be faster. So, this is the surface cooling rate, this is the center cooling rate cooling rate at the core. So, here at any instant this magnitude this delta T in furnace cooling is very small. So, therefore, when it cools two things happen see one there will be thermal contraction and when this transformation pass takes place from austenite to decomposition product.

Whether it is ferrite plus (( )) or it is martensite the material will try to expand and the two or in opposite direction one is trying to contract I mean thermal cooling as a result of coefficient of expansion in at the temperature goes down job will try to I mean becomes smaller there will be thermal contraction and as against that when transformation takes place in the material it will try to expand and if one uses this judiciously one can get a job with minimum amount of residual stress or distortion. Now look at it what happens if you are crunching in water say if you quench in water this is the surface temperature that is cooling rate.

This is the center and here you look at as at any time this is a temperature difference so, here when this has undergone contraction this has not core has not contracted that much so, there will be a some stress this has undergone much more contraction then the core.

So, therefore, you can imagine that surface is trying to contract and here the thermal expansion I mean that contraction is not that much. So, therefore, this will be subjected to compressive stress. So, the core it can elongate also in this direction therefore, this will be to distortion and remind your at higher temperature strength of the material is also low.

So, here this material will deform at lower stress here to deform it since it is cooler you will need higher stress. Therefore, the outside is stronger core is softer so, when you are cooling this kind of transformation takes place. So, there will be some deformation because of the temperature difference and this due to this temperature difference there is a difference in the level of or magnitude of the material property that is yield stresses or different. So, therefore, and one can say that delta T this will increase with the cooling rate look at here this is the temperature difference at any instant between the core and the surface. Whereas, here you see this is the temperature, which is much larger and it increases here this is much larger.

So, this here this job will be much more susceptible to residual stress as well as distortion and you can easily see if we assume that transformation stress is much more critical. You will be able to show easily that here you know the job is here, when this transformation mortensite stacks. So, here it has already the transformation has started and as you cool down here is still the center the temperature is much higher than the in this temperature. So, here the transformation has not started here so, what will happen and here it is strength is lower. So, when it is trying to expand it is trying to expand it will subject to a stress so, we it will be subjected to a stress and it will deform also and towards the end what happens?

Let us come towards the end where here the permanent this has by that time it has reach the temperature different and in fact towards the end we should actually this curve is it is a constant cooling rate path, but when the temperature comes down it will also follow a this kind of a plot. So, towards the end you will find again the temperature become same will be true in all these cases towards this end the temperature this plot actually should come down and go like this. So, again the temperature difference decreases so, that means what happens here this will towards the end of the transformation, but this tries to expand this has already reach it is final size and it will not allow it to expand therefore, here you will have compressive stress.

Here the tangential there will be compressive stress tangential whereas, here there will be tensile stress so, this is acceptable to cracking you can say so, the here you will have tensile stress on the surface. So, it can lead to surface cracking and also as we have seen during the transformation when it is trying to contract I mean initially it will try to contract and then later on it will try to expand. So, in the process some time you may find if you are able to capture the picture or transformation which is taking place it will you will find the dimension and this direction also will change and it can deform or it can contract depending on the nature of stresses that is subjected to. And if your job size is more then also say suppose if it is a much bigger and you want to cool it.

In that case this temperature difference can be much more. So, therefore, these are the two important things to control the residual stresses you have to play with the cooling rate depending on your jobs size and geometry. So, that the material you job which you are giving a subjecting it to heat treatment does not undergo any distortion as well as does not develop residual stresses. Now what are the ways of avoiding others certain transformation heat treatment proceed here where you can avoid origin of such stresses.

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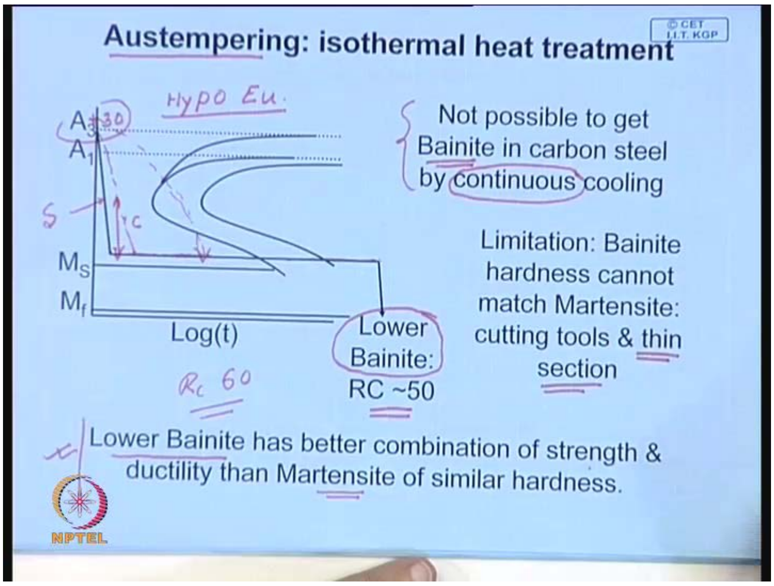

Now if you look at the transformation diagram TTT diagram there were some special types of heat treatment which can be given to jobs of a particular size. One is such isothermal heat treatment proceed here is known as austempering this is an isothermal heat treatment proceed here. If you look at that TTT diagram for a particular this is a hypo eutectoid steel hypo eutectoid steel. You heat it to A 3 plus in around 30 to 40 degree centigrade austanise and then you cool it to a path which is maintain above M s and here you see the transformation at this stage is very slow rather slow much slower then over here.

And if you can maintain it I mean maintained job at this temperature here say suppose this is the rate at which the surface is cool similarly, the rate at which core will cool is something like this and when you hold in during this time both the temperature may be come uniform also and allow the transformation to be completed at this temperature and then in quench. So, the structure that we will get under this condition is a lower then I bainite structure which has equal high hardness this hardness matches with the hardness that you can get under after hardening and tempering.

So, look at this process here if you follow this kind of a procedure you are able to control the temperature difference between this core and this surface to some extend that you can minimize the residual stress that will develop during the transformation process. And also you know this kind of the given this kind of treatment at is also possible to get bainite in a plane carbon steel which is not possible you cannot get bainite structure by continuous cooling. So, that means a low cost material if you can give this kind of a heat treatment, it is a properties are excellent and in fact this lower bainite in certain cases as better combination of strength and ductility than martensite of similar hardness. So, therefore, this is a quite attractive propitiation therefore, but what is the limitation? One limitation is in bainite you cannot get the hardness of the order of let us say R C around 60 which is needed for cutting tools.

So, this hardness cannot be made so, far that kind of application is may not be suitable second is you may not be able to get is completely this lower bainite structure in the job. If the job dimension is large because in that case you may not be able to core may not cool. So, the job is large possibly will find when you are surfaces cooled and that here, but here you may get some amount of find bainite within the core. So, that means another limitation is this treatment can be given only two thin sections. Now another isothermal treatment possess that one can visualize form this is what happens that if you let the temperature to become uniform when you old the job at just say temperature which is little above M s.

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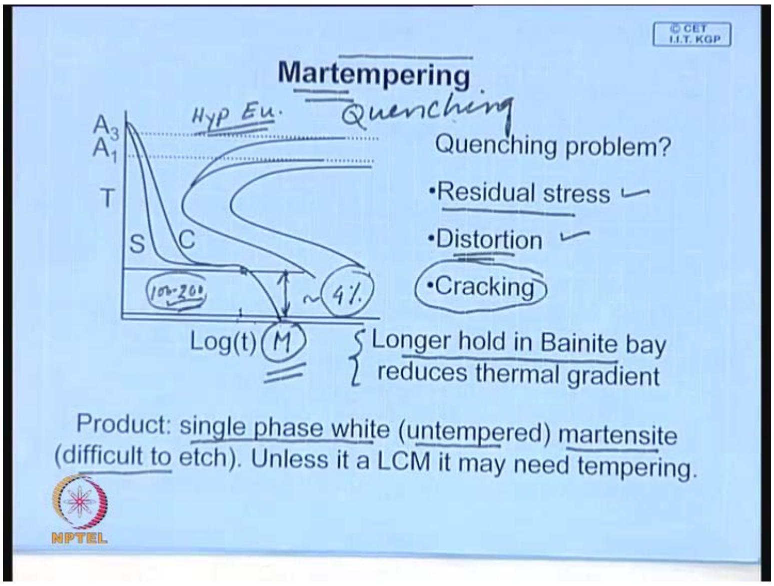

So, that the temperature at the surface and the core becomes equal which is shown over here you cool here and then after that you quench it. So, in this particular case what you are getting you are getting hardness of mortensite to get a full mortensitic structure even in this case of a hypo eutectoid steel. Now second I think you are able to minimize residual stress you are also minimizing distortion also because you are alarming because that expansion is quite sizable, when this transformation takes place from here this is an thermal transformation over a degree of say may be 150 or 200 degree centigrade or 100 to 200 degree centigrade. You have 100 percent mortensitic transformation taking place over this temperature range and here this is a thermal transformation.

So, therefore you know when 100 percent transformation means around 4 percent expansion nearly above around 4 percent size above and this will certainly to residual stress distortion and of this stresses are higher than the fracture stress of this stress necessary to initiate a crack the job may feel it may develop surface track. So, what happens here in this particular treatment you give a longer hold in bainite bay and by holding this your minimizing thermal gradient therefore, your overcoming this stress related problems. So, this temporary is known as martempering or sometime it is also known as marquenching so, instead of tempering you call it marquenching.

So, if you look at the micro structure of the product what it will look it will be made up of untempered martensite. A untempered martensite you mention it is difficult to etch therefore, it will the final product should be single phase it is white, it is untempered and it is difficult to etch and that after that it one pears that you know you combine the term with a tempering it looks that if you do not have residual stress you do not need to temper which is not always true may be if it is a low carbon steel go tempering may not be necessary, but if it is carbon contain is high there is a possibility you know the there will be some retain austenite left in the material and also the structure will be dimensionally unstable it may transform during service which nearly tool change in dimensions.

So, there are particularly in high carbon steel it will be advisable after martempering some amount of tempering may be necessary. Now in all these heat treatment process one or the crucial step is how do you austenise the material and do you need to control the process of austenite digestion.

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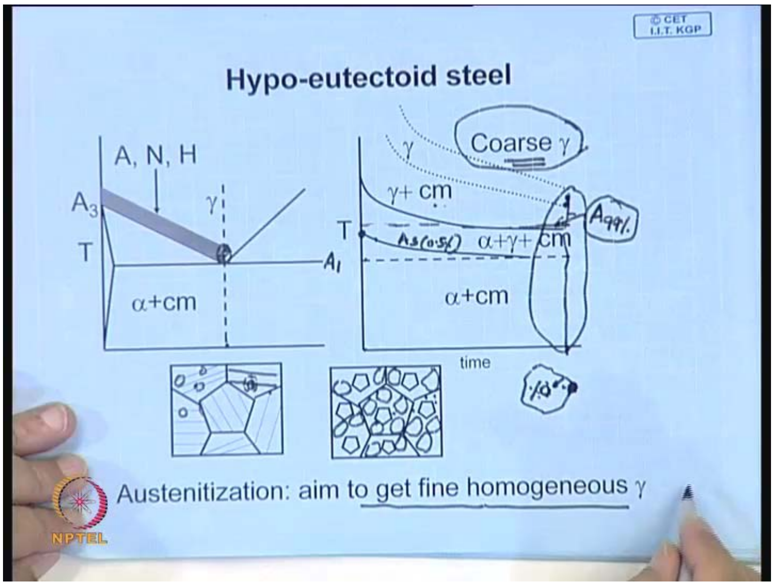

Let us look at it little critically the way that process of austenitization is also an isothermal treatment if you recollect that phase diagram that relevant portion of the tier and carbon phase diagram and let us consider this eutectoid steel. If you heat it your austenizing temperature is here 30 to 40 degree centigrade above of this lower critical temperature. Now here if you keep it what will happen here also you can visualize a similar time temperature transformation diagram we talked about during cooling? So, this is the time this is the temperature your heated it at short time you have put over here.

So, even now although you have heated it transformation does not begin immediately because this conversion of bainite to austenite will be a time dependent process because it means diffusion you have to allow sufficient time for diffusion.

What will happen is if you have a bainite is made up of let us say this plates in a ferritic metrics. So, what we will have is certainly a nucleus of austenite will develop over here and this will try and grow. Similarly, this will develop at several places that will develop and they will try to close something like this. So, this is a time dependent for second period of time you know you have to allow may be this is the time where this transformation starts. So, you can say this is A s say may be here around 0.5 percent austenite has form in the structure and with time is will go on increasing and this you can see here nearly austenite will be nearly 90 percent or 99 percent austenite is over here, but even when you have all this austenite go. So, these are which is pictorial is shown.

Similarly, this austenite you will go up many other places and finally, what you will have so, this is the say it is a tier austenite size what will happen the new that austenite grains which will form they will be finer than to start with it will be finer. You can get a very fine austenite grain, but it is not enough to convert this you have to see that this austenite is homogenous for that you have to allow time. So, over here even after all ferrite is gone you may still be left with some of the places there will be some amount of type particles and dissolve.

So, which you have to allows still times for these two dissolving in austenite and may be this is where that the solution is complete, but after this dissolution is complete within that austenite grain carbon concentration may be different, because whenever there is a suppose just before this process of dissolution is complete there was a same in type particle here so, what happens the carbon concentration surface is more core is less you have to allow time for this composition to become uniform. So, which is shown over here and what is this becomes uniform, now there is no carbide or particles to control it is growth. So, after some time this austenite grain will start growing and it may become if you keep it very long it will become coarse and as will see later.

That is it is a coarse grain structure is not desirable your coarse grain structure they have a poor toughness. So, one likes to avoid it and see if you try and therefore, what is more important is to optimize the condition. So, may be this is why you will see is a maybe you will say 30 to 40 degree centigrade you will keep above this so, which may be say somewhere here and may be this time you have to allow so, maybe just over here before this grain goes you have to stop that is working. So, that you get fine possess aim is to get fine homogenous austenite. And once and this process will be exactly same irrespective of the composition of the steel only difference that may be may come up is the temperature of austenization may differ.

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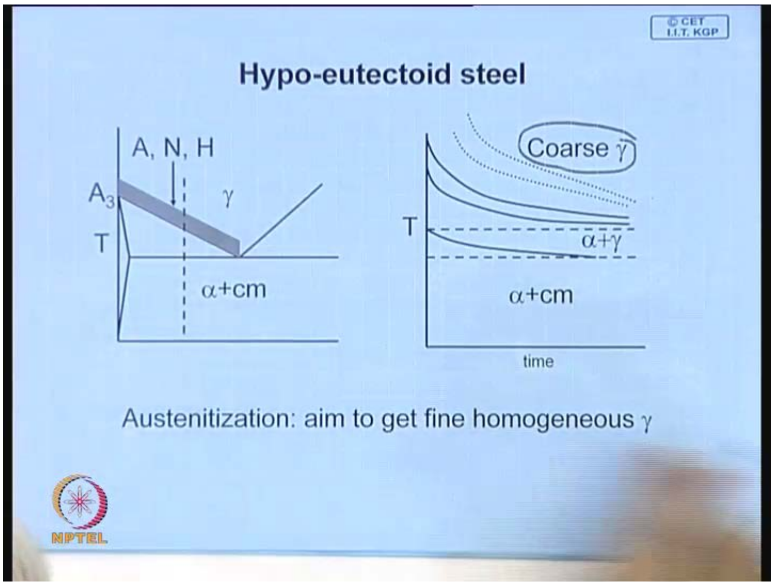

Like hypo-eutectoid steel this is the temperature and here again the similar transformation diagram one can visualize. So, this will be the start you know beginning of formation of austenitic grain and similarly, this is where austenite starts to become very coarse therefore, as similar diagram one can think of in case of hyper-eutectoid steel as well.

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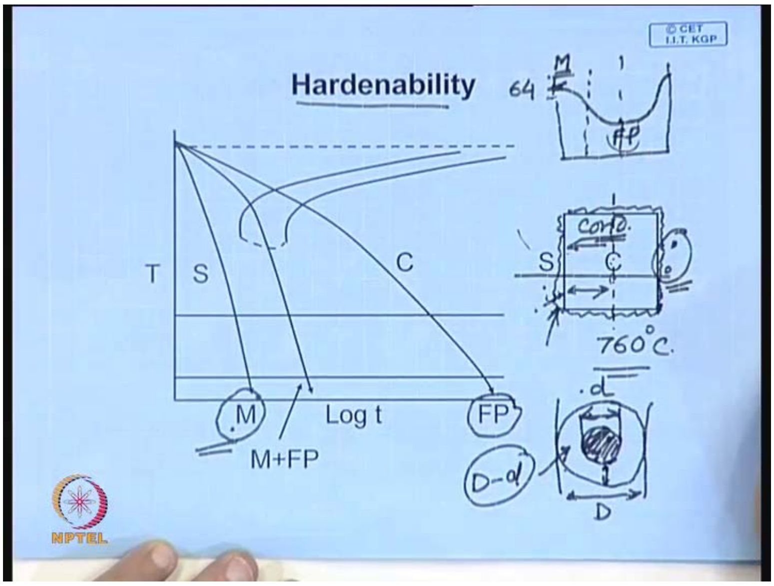

Now let us try and understand we mention about term called hardenability what does it mean so, we just mention that when you quench a job. So, this is a job even if you quenching water it is the surface which will cool very fast, but point is when you quench it in imagine this has a temperature around say if it is say 760 degree centigrade if you are cooling from you depicting cold water, suddenly a blanket of steel will form. Now blanket of steam is actually not a good conductor of heat. So, it will immediately there may be I mean all these you have to somehow break this film.

Then only that means if it breaks then some bubbles will form which will come up so, it will start possibly from the bottom portion and as this steam blanket this appears. So, this is the place where you will have the maximum heat transfer it. So, therefore, you have to try to promote that kind of a heat transfer. So, that means you have to you do not allow steam blanket to form. So, by this it is possible to cool a job I mean we just that what it is important is no doubt it is possible to get a very high rate of cooling it this, but if the job is large you will find that center will cool much slower, because hear the heat will be transfer by conduction only.

Here is a conduction, but outside you can play with it you can agitate you can allow the bubble to form and by valent agitation you can cool this surface quite rapidly and if you plot the cooling rate you may find that here the surface is possibly cooling like this. Whereas, the core is cooling like this so, core you will get a structure made up of fine bainite surface you will get martensite. So, you have surface hard core we soft. So, that means there is if you plot this hardness along this direction if you try and plot the hardness, what you will find this is the job. So, surface you have high hardness maybe it is 64, but as you go to the center the hardness drops.

These curves if it is cylinder you should be symmetric let us say and so, what you have here you have find pilot here you have 100 percent martensite. In between you can think about is structure where it is 50 percent martensite, 50 percent bainite and you know if you after quenching if you take a section develop the micro structure this demarcation is very easy recall martensite is difficult to each. So, what you will find then this is the job the center portion will etch. So, this will become dark, this is bright.

So, what you can do you can measure say suppose you can measure this diameter, you can measure the zone diameter of the zone in which you have a structure or soft structure. So, in this outer periphery this annular region which is D minus d here you have the maximum hardness. Now hardenability determines the ability of a material to harden, we will later come to it what are the factors had determines hardenability, but let us first look at how we can get a more quantitative definition of hardenability it is not hardness. So, in this particular case the job has very high hardness at the surface, but this depth of hardness. If you want to get fully harden structure up to this then how will you proceed?

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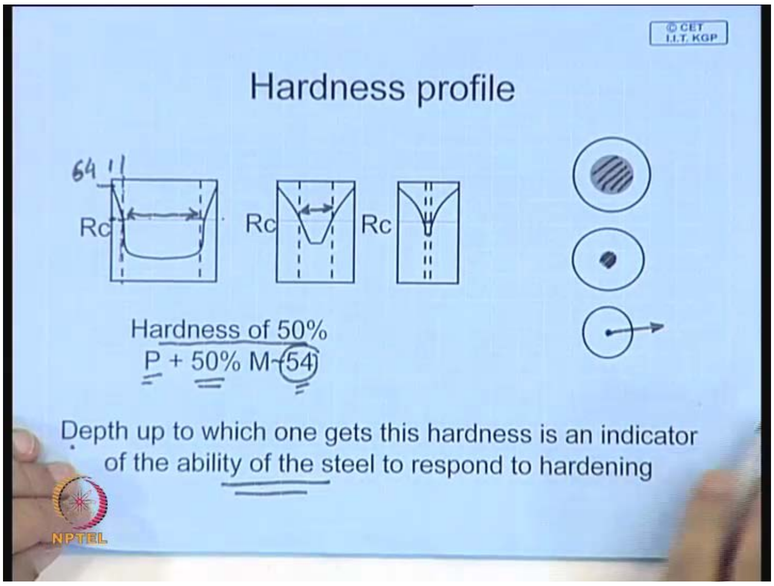

Now if you can do is a very simple experiment take the cylindrical test pieces of different diameter heat them all in the austenitic range and then you quench, and let us say we use a cold water are the quenching medium cold water we agitation and if you quench and now let us see a each after you have quench you cut this samples at the center and you try and a polish and look at the micro structure or the macro structure. You will find say suppose here say this is a little larger diameter, here you find that this is the portion where it is pilatic structure here I pilot if the job become smaller you will find this is the size, if you meet it still smaller this. So, in this way you can obtain to find out the diameter where this disappears. This is a non existence this does not this just disappears.

So, this in the best way to think about it is when you take a section you can measure this hardness from this end to that end, this is the hardness profile, this is let us say this is hardness 64 at the surface and 50 this martensite hardness that this mixture 50 percent bainite 50 percent martensite this is around R C 54 for eutectoid kind of steel. So, around carbon contain around 0.7, 0.8 this hardness have 50 percent martensite, 50 percent perlite will be around this. So, look at where you have when you say this is my depth of hardness whereas, this is diameter if you measure, this is the dimension of the core region which you have not been able to harden.

So, one way you are defining in this hardenability this is a measure or give some idea to what does one gets this particular hardness or you can say this depth is an indicator of the ability depth of hardness is an indicated of the ability of the steel to respond to hardening and this also one you can say maybe one of the definition of hardenability.

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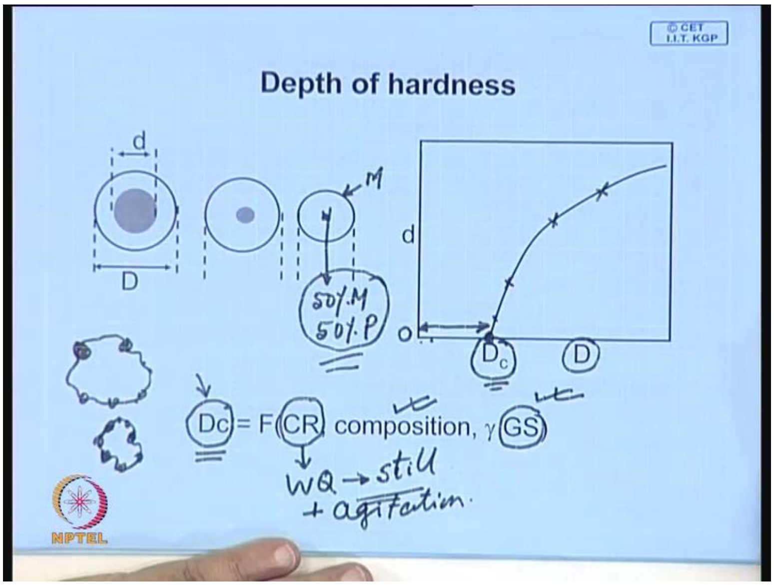

Now let us try to have a little more quantitative definition if you plot this diameter say if you have measure this diameter you may keplon this diameter against the diameter of the job so, you gets a different points here. You have a large number and then try to extend it to a region you know finally, you find this is the dimension where this D is 0 so, what it means with this quenching procedure you in a particular material which you have taken the steel you have taken if this diameter is less than this critical diameter then you will be able to harden it through and through.

So, that meant what is says in this particular diameter you will have surface fully martensite 100 percent martensite and in the center you will have 50 percent martensite, 50 percent perlite and for all practical purposes one takes this has the fully harden structure. Now obviously the reason that comes up is what is the I mean what have the fact is determines this critical diameter. Obviously, one is the quenching medium that you are using that cooling rate. So, if you or doing say quenching in water quench may be it is still water no agitation. You will have one value and once I mean when you quench in water plus agitation.

If you agitate rigorous agitation then you will find that this critical diameter will be higher. So, this is not you cannot say that this is some kind of a material property it depends also on the composition of the steels a particularly the carbon content and as will see later it also depends on the presence of other alloying elements. So, depends on the composition of the steel it also depends on the austenite grain size. Why should it depend on austenite green size we will look at it more critically later? So, if you have a large grain of austenite then you can see that to harden you have to surface diffusion control transformation; if you have a course austenite grain the site where paralite not use can form they are limit if they can form only here.

So, here only here perlite not you will can form. Whereas, in if you have a fine perlite here the number of places the frequency of the size or much more number of sites at which deform or transformation can take place is much more in fine austenite whereas, in course austenite this is much less. So, therefore, diffusion control transformation here will be slow so, this is also an important factor that will determine this critical diameter, but typical diameter is still you know it depends on the cooling rate.

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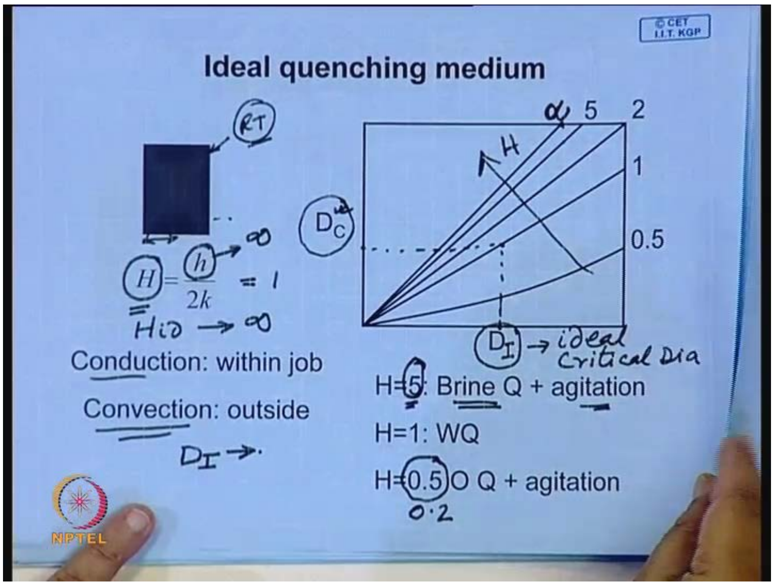

Now the questions come can we have it which is independent of cooling rate. So, this to be first attempt to define a proper quantitative definition was given might option. What is hot is visualize a quenching medium, which is an ideal quenching medium, and what an ideal quenching medium, when you quench the job in water say from 760 in cool water. So, you are decreasing the surface drastically now if you think of an ideal medium where when you quench the surface temperature comes down immediately to let us say room temperature. This surface temperature immediately comes to room temperature or 0 degree centigrade.

Let us say immediately comes to the temperature, where transformation is complete below and a temperature in that case, what is happening? Now the heat transfer is totally determine by two things is one is this conductivity, but for this you have to have a very infinite convective heat transfer coefficient, because the major mechanism of cooling here will be convection over here and the water conduction within the job. So, what we can think about that a quenching seniority parameter defined as etch and this we take it as a ratio of the heat transfer coefficient the convective heat transfer coefficient H and this is the conductivity of the job h by twice k it define as a quenching severity.

So, steel water you defines maybe steel water quench. Normally you take H as 1. Whereas, ideal medium this is ideal quenching this is infinity, but as infinity means that means heat extraction rate by convection is infinite is very large much larger than this case so, this is an hypothetical quenching medium. Then you can define people can do some measurement actual experiment measurement and have try to find out like this brine quench if you put some salt in water then the quenching rate becomes much faster. So, brine quench with agitation has this quenching severity 5 whereas, if you have oil quench with agitation we will have this may be oil quench without agitation will be much less sever may be 0.2.

So, this is how it is possible to define Gauss man introduce the concept of quenching severity, but there are lot of later development if you have time we will look at, but little later. There most important factor therefore, is to convert this ideal this is critical diameter, which you are measure for a particular quenching medium how to converting to a parameter which is independent of cooling rate. So, what you did is if you define this is another diameter that is critical diameter when you quench the job in an ideal quenching medium D I. So, this is called ideal critical diameter, Ideal critical diameter define the relationship between D C and D I therefore, if you can draw such lines these are obtain evaluated experimentally that ideal quenching medium has infinite quenching severity.

So, this is thus whereas, here this is the 45 degree line as the quenching severity decreases so, H decreasing. So, H is increasing in this direction so, as the quenching severity decreases you will find that if you have found out this critical diameter by say let us see by water quenching here then you can say that an ideal critical diameter will be higher than D C. So, in all cases you will find that this is therefore, ideal critical diameter is a dimension of the job is the maximum dimension of the job if it is quenching from the proper austenizing temperature then it will harden through and through. That means it will higher 50 percent martensite, 50 percent perlite at the center and 100 percent martensite at the surface.

So, this is a definition of hardenability one can say ideal critical diameter is a good definition for hardenability. Now the question that comes up is this procedure of determining hardenability is quite D s. You need a large number of sample they have to be quench they have be cut and you have to prepare the micro structure to very time consuming process. So, can there be a method by which you can determine hardenability of steel quickly, because unless you determine this hardenability it is very difficult to design your heat treatment procedure that quenching sequence the rate at which you will cool.

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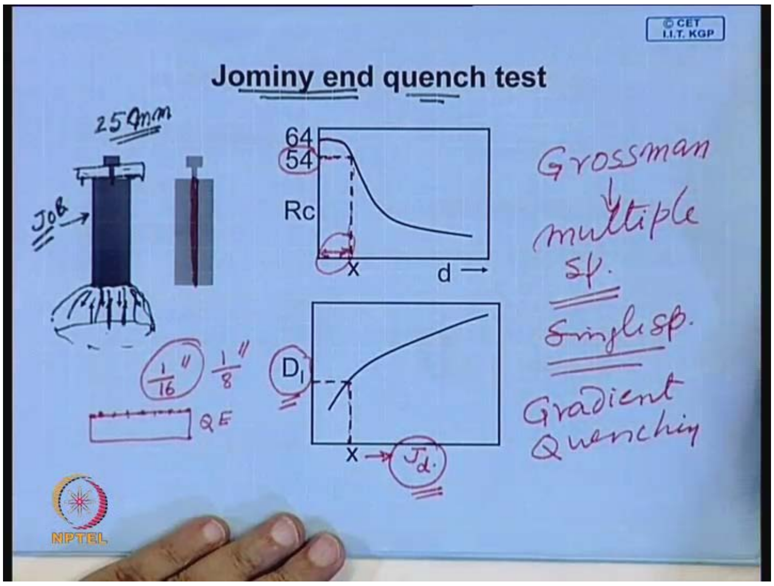

Let us see one such method of determining this hardness by a single specimen, this is called Jominy end quench test. So, we talked about austenite grain size measurement you know in an one of the earlier lecture where if you can give a gradient quenching so, what you do you have a job here that is a part you know which you can I this through does it so, this is your job. That is a provision to fix it on a cooling fixer so, this is or this can be a single part also or sometime you can have a caller give a caller here which can be put on a rig. So, main part is this and the diameter is around of this is around 25 millimeter around on inch in diameter. Summary 2.5 inch long depending on that hardenability that you expect.

Now what you do you heat this entire job to the proper austenizing temperature and after it has been austenitize you take it out put it on a rig and this support and then try to cool this end by spraying water cold water you keeps spraying. So, when you spray it comes out the water comes water goes in this direction and comes out in the form of an umbrella kind of thing, it comes out at forms. So, why this what you are doing you having the highest cooling rate here lowest cooling rate at this end so, what you have is a gradient cooling and then what do you do after it has been cool to temperature take out this sample and you polish a grinded small portion here. These ends this actually indicates is now what you do you press this in a Rockwell hardness testing machine.

So, there are normally this you can put it on a Rockwell hardness testing machine and you have indented and there are also device is you start measuring this hardness maybe so, this is the quenched end you start measuring hardness from this end add some regular interval and all these dam many of these equipments which are you use there are thing where you can move it that there are stage which can be mounted on the Rockwell hardness testing machine and by rotating one cycle you can move the job by a fixed strengths and usually this maybe 1 by 16 of an inch or 1 by 8 of an inch. You keep moving and then and you get hardness from the quenched end to be other end.

Then you make a plot you will find you get a plot like this, then you can say and look at place where you get hardness 54 then you can say this is the depth of hardness in a Jominy end quench test and once you get this there are now experimentally determine conversion charges which are available. So, once such graphics here and what you do look at this is a graph this is the Jominy test hardness deft. This is Jominy hardness deft, which you are measured and look up this chart and this chart will give you this is the ideal critical diameter. So, therefore, what you do here?

So, here is a method by which you can determine hardness in a very by a single by performing test on a single specimen. So, compare to you know the gross men method, where you need multiple specimen and what you are using you are using gradient quenching method.

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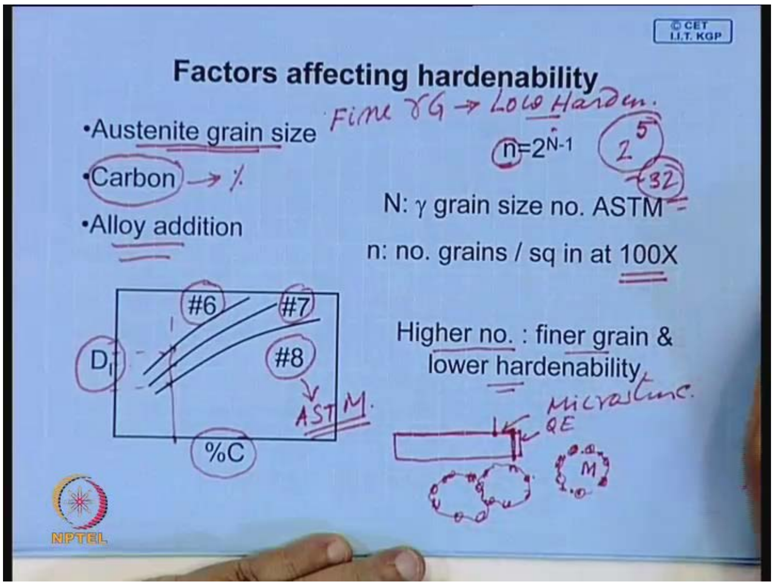

Now a point about the factors that determine hardenability of steel; what are the factors? We just mention that one important factor is the austenite grain size and let us see what are these factors and how do you determine them. So, one way is this austenite grain size I think this method determining austenite grain size was talked about earlier even it is possible the Jominy end quench test after you have measure the hardness. If you try develop this face develop micro structure develop micro structure. If you look at the micro structure the someplace we will find there are the austenites these paralite modules which exist around appear austenite grain size. So, go here this portion is martensite so; this will happen say if the Jominy end quench the deft of this is the quench end. So, some where here this is 50 percent martensite.

So, here it will be very difficult to find out where austenite grain size, but somewhere here you may find out a micro structure where you will get say it is this these are the diaustenite grain size will be mark by this parlitic modules modules of parlite. We have just seen that if this austenite grain size is fine grain size has low hardenability. Fine grain, fine austenite grain then low hardenability. Now another important factor is said is a composition one of the prime composition is carbon contains.

So, if you have carbon in the steel that carbon contain percentage carbon few increase, the hardenability increases this is quite obvious if you increase carbon contain we mention time and again that the transfer diffusion control transformation becomes slower that CCT diagram shifts to the right at high temperature end therefore, you will be able to get full mortensitic structure with the much slower cooling. Later on we will also seen that alloy addition also addition of other alloying element also affects hardenability. So, to some of what you can see that this hardenability is defining in terms of ideal critical diameter if you try to generate it plot or this hardenability this ideal critical diameter as a percentage carbon you may be able to generates such plots.

Here we have put certain numbers these are austenite grain size is define in terms of numbers call ASTM grain size number and how do you define this number? This is the number of austenite grains per unit area and this is an exponent 2 to the power N minus 1. Say suppose if N is let us see 4 this or let us see this N is 6. So, 6 minus 1 this will be 2 to the power 5. So, this is 32 so, 32 you will get 32 number of grain if you look at the micro structure at 100 magnification, but in that field you will see 32 grains of austenite per square inch and all these procedure where device at time where this inch actually many of these defined in terms of inches many of these dimension it is possible to converted but that is for I mean to maintain that SI unit, but the point is that means per unit area the index represents number this minimize represents number of grains per unit area.

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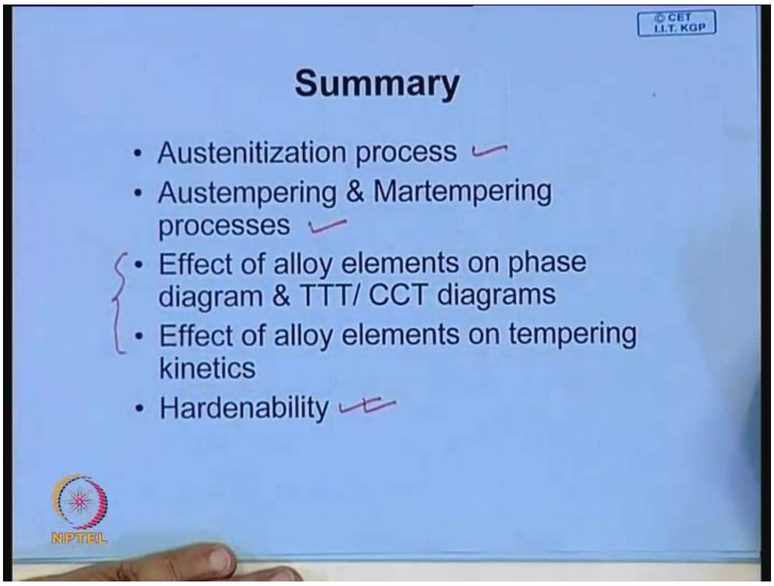

So, if you look at this over here for a given composition if the grain size is coarse this ideal critical diameter increases. So, this is where it is a finer austenite grain size it has lower hardenability that we always prefer fine austenite grain. So, just some of here what we have covered today is austenization process. We looked at two important isothermal transformations it will the isothermal heat treatment procedure or austempering and martempering. We have looked at hardenability little details, I think what we miss this and maybe we will consider this in that next class. Thank you very much.

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