Principles of Physical Metallurgy

Prof. R. N. Ghosh

Department of Metallurgical and Materials Engineering

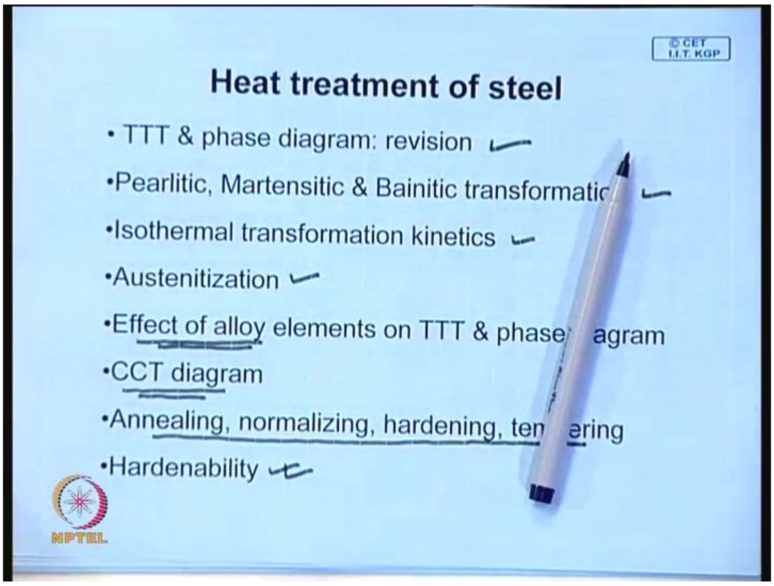
Indian Institute of Technology, Kharagpur

Lecture No. # 36

Heat Treatment of Steel (Contd.)

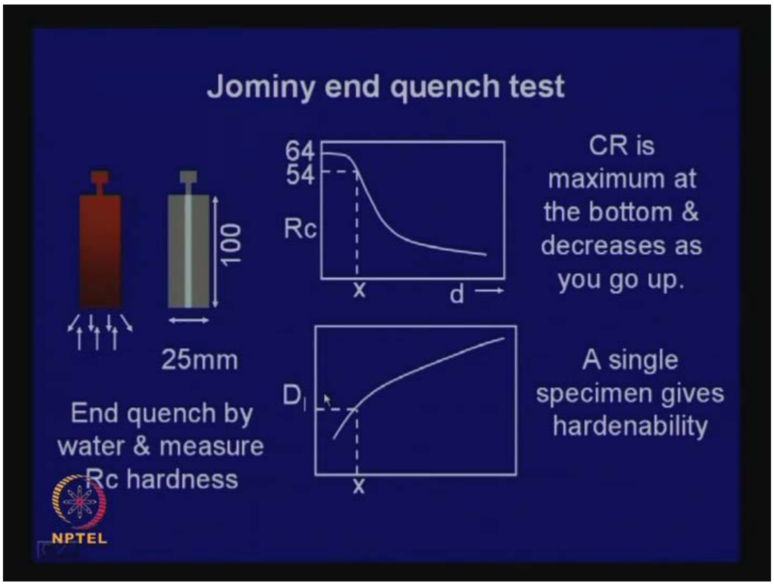
Good morning last several classes, we have been talking about heat treatment of steel, and today we will try to finish the points I mean which has not been discussed so far.

(Refer Slide Time: 00:39)



If you look back, you will find that under this lecture, we have covered this, we talked about this isothermal transformations. We talked about isothermal transformation kinetics, we talked about austenitization process, we talked about CCT diagram how they are made, we talked about some common heat treatment processes and part is which is left out, I think last class we introduced and discussed hard enability. Today, we will see a little more some important aspects of hard enability, and we will also try to look at how alloy additions - means other than carbon how does it affect the transformation diagram both TTT, CCT and phase diagram.

(Refer Slide Time: 01:37)



And if you try and recollect the previous thing, we introduced a this Jominy hard. So, we introduce the concept of hardenability, and it was told that hardenability gives you a measure of the depth of hardness, that you are likely to get if you austenitizea piece of steel. And then quench an certain medium or cool at a certain rate to what depth, you will get the desired hardness that you all looking for and we define certain factors like quenching severity, how do you define coolingrate.

So, we talked about a factor called h factor, gross men severity of quench factor and we also talked about ideal critical diameter, which is a material property in a way. So, this gives you the depth of hardness, that you can get in a steel if it is quenched from the appropriate austenitising temperature in an ideal medium, where you have infinite severity of quench. Then D I is the depth up to which you will get complete hardening and complete hardening does not mean that the hardness is uniform from surface to the center of this job, but it means that you have hardness at the surface, which is the maximum hardness. At the centre, you have a hardness, which corresponds to 50 percent martensite and 50 percent transformation product and for 0. 8 percent carbon steel hardness of this 50 percent martensite, 50 percent pearlite is around 54Rc or around 55Rc.

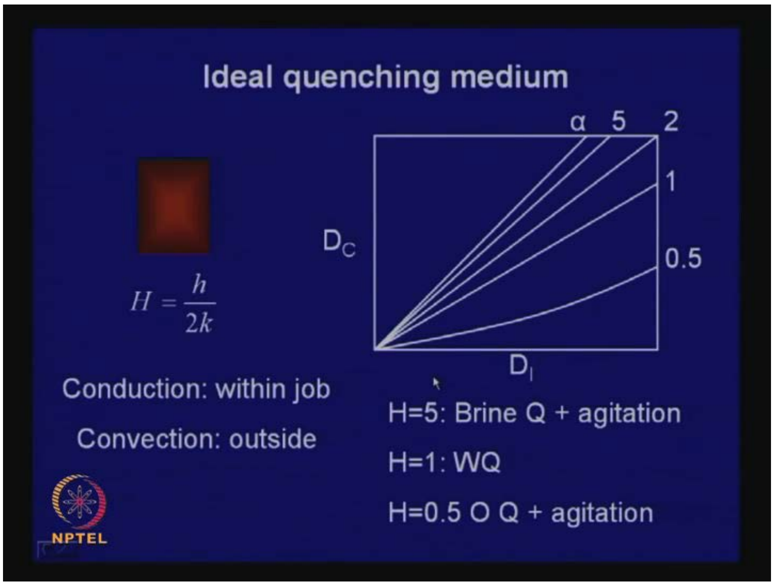
And, since to determine ideal critical diameter by following gross men method, you need a very large number of samples and the test procedure is also quite involved and time taken. And a quicker method is a jominy end quench test, where one uses a gradiant quenching, and here you will find that is the pictorial represent at ionred, when it is hot, and you are trying to cool the bottom by spraying water. And you spray water from a certain fixed distance and it touches the surface and falls out in the form of an umbrella like a curtain kind of thing.

And so this is where you have the maximum cooling rate and the cooling rate decreases as you move along the length. And here you have the less minimum could this end will be the minimum cooling rate and after the end quenching is done after the sample has cooled down to room temperature you take out this piece from this picture. These specimens also this dimensions approximate dimensions are given and these test are actually empirical test.

So, it is better to follow this standard dimensions which are given here and then what you do you grind a make this point smooth. Since, it is round, it is a cylindrical sample and you grind of the top surface and along this surface, you keep measuring hardness at different distance from the quench hand and after that, you make a plot this hardness against the distance from this bottom and if you plot, you get a hardness profile something like this.

And then say this is the maximum hardness that you will get near the surface, where you have the maximum cooling rate and somewhere down below you find out where it is the hardness corresponds to 50 percent martensite, 50 percent pearlite say 54, and then you say that this is my depth of hardness. And in fact you know that this test is the single specimen test and this became, so popular people have worked out and found out correlation of this jominy hardness depth. And this is the jominy hardness depth X and this can be converted into ideal critical diameter, and in fact these are such type of plots are available, and which converts, which helps you to convert the jominy hardenability depth, hardness depth to ideal critical diameter. So therefore, this is the most popular method for determining hardenability of a particular steel.

(Refer Slide Time: 06:37)



Now, we introduce a concept of ideal quenching. Let us look at it little critically you have a sample here where what is shown you know I have tried to quench and surrounding you know it is surrounded by water, it is quenched in water so it does not; temperature does not immediately come to room temperature. Definitely the surface will be at the lowest temperature centre will have the highest temperature and with time the temperature difference will go on decreasing and the rate at which will decrease will determine our ability to extract heat from the surface which will be determine from convection. That means within the water, how fast we are able to take out the heat and within the job this rate will be determined by conductivity or conductivity of the material rate at which heat can flow from center to the surface. And obviously this convection heat transfer so there will be so we define a severity quench by factor.

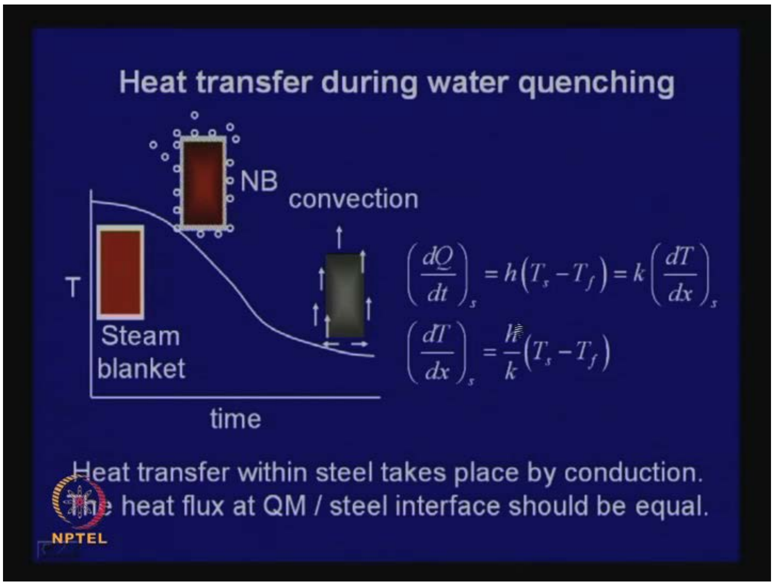
So which are defined by gross men it is a very average heat transfer quenching severity which is taken as a ratio off which is the convective heat transfer coefficient and over twice the thermal conductivity of the material. So, within we say that ideal quenching medium is one where H is infinity what does it mean the small his infinite.

So that means as you quench, what we can say that immediately this surface comes to that heat transfer this is infinite. What we can say the surface immediately comes to the temperature of that surrounding say if it is the quenching medium. So, that is the maximum that we can think of, but we will little while we will see that it is far from reality, but nevertheless many cases one does define such cases where you have very extremely higher infinite, it is a hypothetical quenching medium where his infinite. And I leave it to you to examine the dimension of the heat transfer the H. We will find this dimension comes out to be one over length.

So, most of these heat treatment still people report many of this charts you will find people use inch as their measurable distance, but we change one inch is equal to roughly 25 millimeter. So this such approximations are always used in engineering. Now if we you try to find out, so this will be 1 over a in chor 1 over a meter or 1 over a centimeter that will be the dimension of the severity of quench. And here we have listed some of the common severity of quench say brine with severe agitation you can get H is5 and H is 1 for a normal water quench without agitation.

Whereas if you oil quench, in that case it can be depending on whether you have agitation or no agitation have certain value for this quenching severity like 0. 5 for oil quench with agitation. And here you have a chart which gives you the relationship between the critical diameter and ideal critical diameter. And this is the plot for infinite quenching severity that is H is equal to infinity and you will find that this slope of line is one. So that means if D c critical diameter is one, D i is also one, whereas in other cases; if you find that for a particular material that D i you find that it is say 2 inch or something which is somewhere here. And then if you quench inoil, then you can find out this is the depth up to which you can get practically speaking that means that up to that depth you get hardness corresponding to 50 percent martensite, and 50 percent pearlite which is definitely much lower than the ideal diameter.

(Refer Slide Time: 11:37)



Now a quick look at the heat transfer process of heat transfer when you quench and let us see, look at it little more critically say here if you quench, this is a section of a job, which has been quenched in water. When you quench it has a very high content of heat so suddenly what happens, a blanket – a steam blanket will form over here. And when a blanket - steam blanket this has a relatively low conductivity and it is stagnant, so you have a poor heat transfer coefficient.

Therefore, here you find as long as the steam blanket stays, you have the rate of cooling is slow. So this is the region and the rate of cooling starts increasing once a bubbles nucleate and this bubble nucleation excepts in severe or violet agitations in this surrounding area. And once this nucleate this is called the nucleate boiling. And once this nucleate boiling starts, you have bubble formations which results in severe agitation and therefore, the cooling rate increases substantially.

So you have maximum cooling rate in this region and later on when this boiling stops, then the normal convection takes over. So this is the case of a normal convection and it may take a very long time to plot that cooling curve, it may have a something behaviour may show like this. There are three distinct regions, where you have steam blanket, which prevents its transfer say slow rate of cooling, then nucleate boiling then this is what one should try to get as quickly as possible to get an ideal quench and then finally convection. Now, the point that comes up here is purpose of cooling is you have to organize, I mean the heat extraction rate must balance the way rate at which, you are able to extract heat from the surface by this convection; this is from outside convection or nucleate boiling or whatever is the mechanism the rate at which you are able to extract it, must balance the rate or that heat at which heat that flows from centre of the job to the surface. And therefore it is possible to apply this concept of heat transfer to derive some very simple relationship.

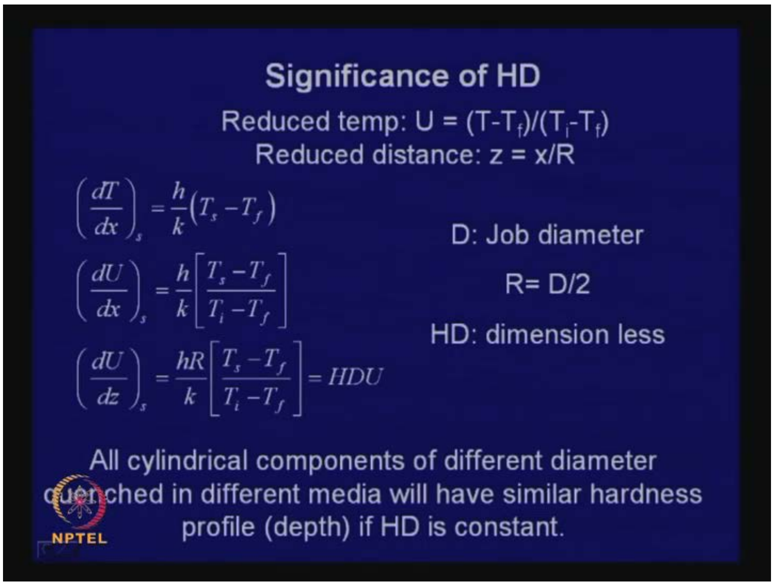
Now which is listed here this gives the rate at which the heat transfer, this is the decade amount of heat flux, which comes out from the surface. So which will be proportional to the temperature difference T f you can say is a final different temperature of the job or you can say this is the temperature of the quenching medium. So, let us say this is the room temperature and this is sis the surface temperature at any time at any instant.

So, if you say that it is the initial just you quench, you can say that this temperature is the austenitization temperature, which arrived at T equal to 0; this is the temperature whereas, at any instantor you can say this is the temperature which is the function of time, and h is the effective heat transfer coefficient. And what you can see here transfer coefficient you know it changes with the time depending on the actual mechanism, but gross men approach you know it assumes a constant or you can say an effective heat transfer, and let us assume that it has an average or effective heat transfer coefficient.

So this is the part that heat, the rate at which the heat you can extract from the job by convection from the surface, but the maximum amount of heat from I mean that you can extract through convection is also balanced by the amount of heat that comes from the centre of the job and this is by conduction. And which is given by the temperature gradiant, temperature at the surface minus temperature at the centre. So this gradiant, and this should balance and this is proportional to thermal conductivity. So, therefore temperature at the surface the temperature gradiant at the surface therefore, this x is the distance within the job.

So, the temperature gradiant at the surface you can say is a function this is how you can represent x is the distance, distance from the surface and this is can be written like this. Now, heat transfer within the steel of course, within the job it can be solved by normal heat transfer conductive heat transfer technique which is quite well establish and it can easily be done by Fourier series kind of solutions. But let us look at the much simpler approach which will be quite useful in designing a heat treatment process.

(Refer Slide Time: 17:25)

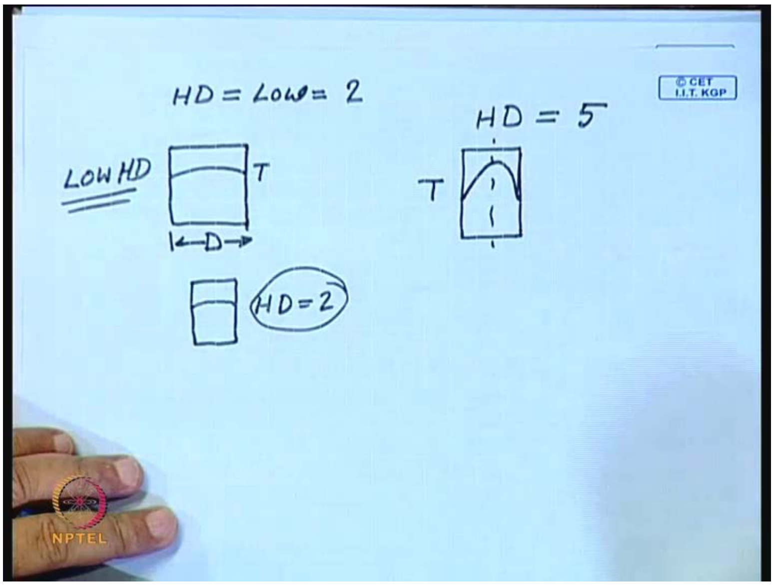


Now, here often one uses you know in heat transfer one uses some normalized temperature, normalized distance, and what you can think about a normalized temperature U, which is a difference of two temperatures, this is the temperature at any instant or temperature surface at any instant T minus; the final temperature divided by T i, which is the initial temperature that means austenitization temperature. This is initial minus T final – final temperature means the temperature of the surrounding or the temperature of the quenching medium.

And reduced distance one can say that x you can say as the ratio of z is the reduced distance is the x of radius of the job or half the thickness of the job. And if you do the simplification you know this expression will transform to this and finally, you write with dU dz this reduced distance you get this term. Now look at this what you are getting here say h over twice k we have assume this to be these verity of quench H as defined as h over twice k. Now, look at this here if you go back here if you divide this by two, it becomes twice R here.

So, h by twice k is H severity quench and times diameter two R is the diameter so this entire expression reduces to quenching severity diameter of the cylinder times U. So, now look what is the dimension of HD. HD H is the dimension, H we have said that it is one over distance or one over centimeter and diameter that is the centimeter. So, HD it is a dimensionless constant and it is a quite a useful parameter in designing heat treatment, and you will find that all case says you know all components, if you find that HD has magnitude is same then what you can say the relative cooling characteristic will be similar. Therefore, all cylindrical camp say of diameter if it is quenched in medium such that HD is constant they will have relatively similar cooling characteristic and what does this mean; so this mean that if you have; let me take a sheet here say suppose if you have a job here which has a particular diameter.

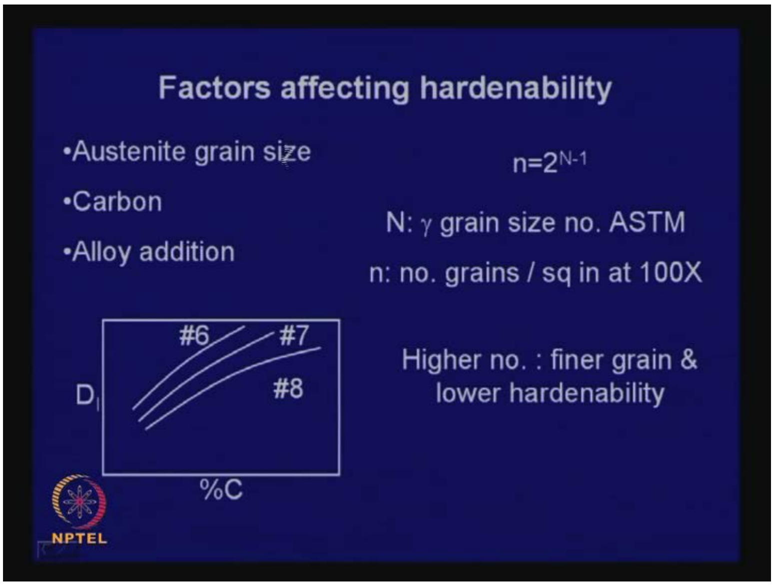
(Refer Slide Time: 20:46)



This is the diameter and that is you have quenched in a medium that this product H time D is low. So, in that case HD in any case, whether if the diameter is this or diameter is small that HD is same so here also say, suppose HD is equal to2; here also HD equal to 2. So, depending on if it is low or high it will determine the nature of the temperature profile that you have, if the HD value is low that you have this profile will be swallow low profile HD. So, here also if you maintain the same low HD here also you will get a similar low profile.

So, characteristic that relative cooling will be same so using this concept, but if HD is high you will find the other end. If HD is high say, suppose you have it is 5, in that case you will find there is a large symmetric so this temperature gradiant. So this temperature here you have a sharp temperature gradiant and it is possible so this is a very simple concept which helps you to design quenching process and then this quenching technique so that you get the desired hardness with minimum distortion.

(Refer Slide Time: 23:05)



And let us now look at the factors that affect hardenability part of it was explained last class, and there are primarily three main factors which determine hardenability one is austenite grain size and we talked about determining austenite grain size ASTM method is like this. And n is the number of grains you see at 100 magnification at 100 X and n represents number of grains in one square range, and this is n is an index which is a number.

So, n means let us say if n is 6 number of grains which you will see in one inch square that will be 32 grains you will find. So, higher the number that means finer the grain, and we have seen that if you have high number of high austenite grain size or high that austenite grain size number. So that means that it is finite grain structure if you have a finite grain structure, you have large number of nucliation size for diffusion control transformation to take place. So therefore, finer grain will exhibit lower hardenability which is shown over here, and last class I explained diagram about effect of grain size on hardenability.

So this is the plot which shows the ideal critical diameter as function of carbon content so that means for a given grain size austenite grain size say, austenite grain size number 0. 8 what it shows that if you increase percentage carbon ideal critical diameter goes up and for the fixed carbon say, let us say 0.5 over here. And let us say for the fixed carbon increaseas you increase make the grains closer or if you control the austenising time. If you keep it for longer time or if you keep it at a higher austenising temperature go higher grain you will find as the grains become coarser the hardenability improves, and this is not favourableway or technique of improving the hardenability, because coarse grain strucutures have poor mechanical propert. And we have talked about it earlier you get a poor toughness and toughness is an important criteria for material selection; therefore, generally even in hardanable steel one would like to have fine austenite grain size so this is not a favourable way of improving hardenability. Therefore, we do not consider this, so only two factors, which can improve hardenability by increasing carbon content and another is by increasing alloy addition.

(Refer Slide Time: 26:21)

Effect of alloy element

%	C#6	C#7	C#8	Mn	Si	Ni	Cr	Mo
0.05	0.08	0.08	0.70	1.17	1.04	1.02	1.11	1.15
0.10	0.12	0.11	0.10	1.33	1.07	1.04	1.22	1.30
0.15	0.14	0.13	0.12	1.50	1.11	1.06	1.32	1.45
0.20	0.16	0.15	0.14	1.67	1.14	1.07	1.43	1.60
0.25	0.18	0.17	0.16	1.83	1.18	1.09	1.54	1.75
0.30	0.20	0.19	0.17	2.00	1.21	1.11	1.65	1.90
0.35	0.22	0.20	0.18	2.17	1.25	1.13	1.76	2.05

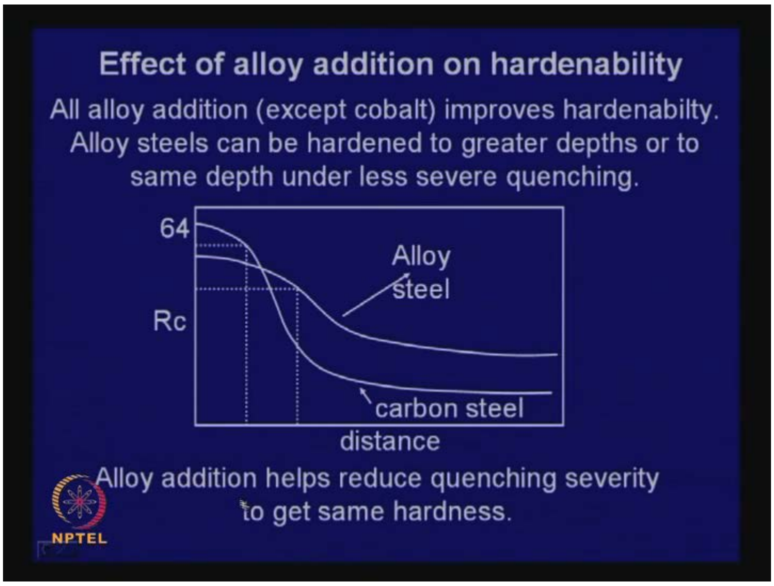
$DI = f1 \times f2 \times f3 \times f4 \times f5 \times f6$

Now, if you look at the effect of alloy addition on hardenability; people are this is empricallyderived results from hand book. And here this column gives percentagewith percent carbon given this approximate value, different austenite grain size number this, carbon with hardenability with carbon plain carbon steel containing a particular amount of carbon, that having austenite grain size number 6 and this isaustenite grain size number 8. So far a given carbon content you find that look at you have a coarse grain say look at over here the coarser grain has higher hardenability.

So, this is a factor hardenability factor so this has a you can say, higher hardenability say 0. 22 is a factor you can say whereas, here it is 0.18, so that means up to 0.22 inch you get a proper hardness; whereas, in this particular case upto 0.18 inch if the grain size is fine. Now, any alloy element you add they help or they improve the hardenability and most of the alloy elements additions; and in fact, one of the primary reason for adding alloy element to steel is to improve its hardenability. As you see suppose, manganese if you go on increasing manganese so these are the hardenability factor see at 0.5 percent and this is the synergy at 0.5 percent carbon steel the factor is 1.17. But its effectiveness increases amount of carbon increases with 0.35 that is the synergy that and that same amount of that they that for 0.5whereas, here when you have a 0.35 percent manganese and this is this and always that need not necessarily believe here these are the values. So, this is if you had 0. 5 percent carbon this is your hardenability for effect increases ability for of manganese to increase hardenability of the steel by this factor 1.15, if it is 0.1 then this factor is 1.33 likewise this is for silicon.

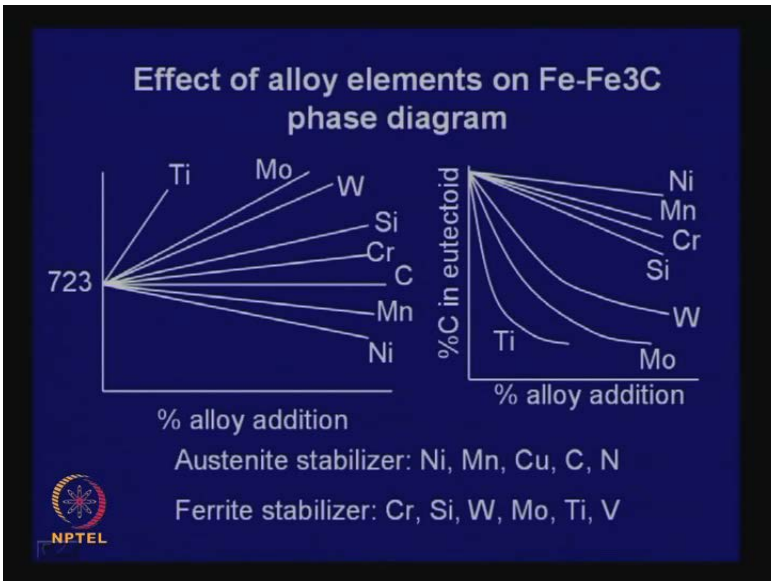
So, compared to silicon the ability to increase hardenability by manganese is higher can see here; see for 0.35 percent for manganese or silicon you get a higher hardenability factor. So, this is the factor for nickel, this is the factor for chromium and this is the factor for molybdenum. So, most similarly, you will have factors for each all the common alloy elements available in the form of table, and if you want to find out the hardenability in terms of ideal critical diameter you have to look information you have to provide the austenitization in size carbon content. And other alloy additions which there are, and then you can look up table say like, if one you look up is austenite grain size number is 8 and carbon content is 0.1, then this first factor is f 1 is 0.1. Then you check up how much manganese it has; if it has 0.3 manganese then you have to multiply f 2 is two multiply this by two. Similarly, you find out factors each of this and you get a value magnitude for DI.

(Refer Slide Time: 30:37)



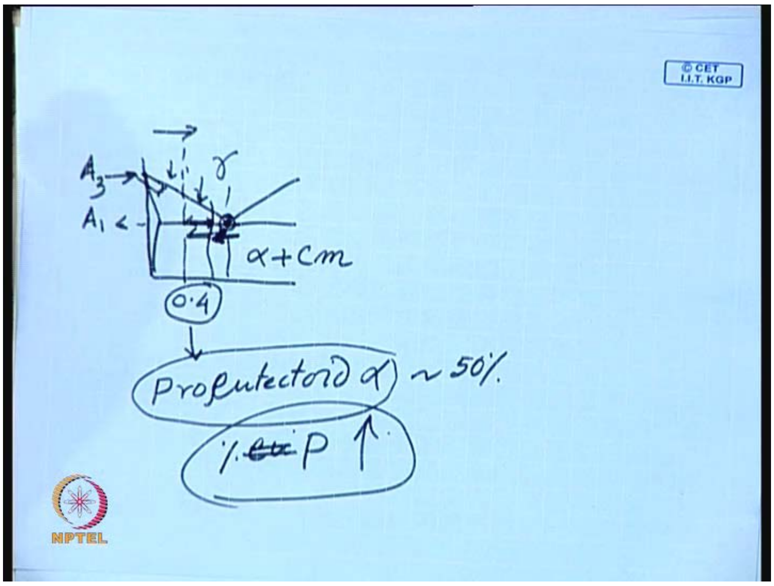
Now, effect of alloy addition of hardenability as mentioned that with the exception of Cobolt or alloy element improves hardenability. And now but hardness depends primarily like carbon content, which is shown in this plot over here, so this is the carbon steel which has the relatively low hardenability, if you look at the jominy hardness part is the surface hardness. Let us say, that this is 0.6 percent carbon steel with no other alloy element primarily carbon will be a shallow hardening steel. And this is the plot the jominy hardness profile whereas, if you have a steel with alloy content possibly here with the carbon content is low. So, carbon content is here and then that the depth of hardness is much more with alloy content. So that means, alloy addition and in fact one of these main advantages alloy addition helps reduce quench severity that is required to get the same hardness at a particular depth.

(Refer Slide Time: 32:01)



Now, let us see why does all alloy element addition you know why this affect the heat treatment procedure here. Now two things an alloy addition will do; one it will alter the phase diagram and second it will alter the transformation diagram.

(Refer Slide Time: 32:29)



And say, phase diagram means say this part if this is the steel say normal carbon steel say this is gamma, the alpha the cementite, but if you will add the alloy element what will happen the temperatures it is no longer the binary system it becomes the ternary or the quaternary system. Therefore, the phase diagram the nature change and let us not go into the total complications of ternary or quaternary diagram, what we can visualize is the critical temperature for example, this is say 0.4 percent carbon steel if alloy addition is added what will happen to its microstructure how do you interpret. And then we can see that alloy addition what does it do it can do two things it can change the critical temperature it can change this temperature A 1, and also change these temperatures A 3temperature it can also change the composition of eutectoid.

So let us first look, at it which is shown over here say, effect of alloy elements, depending on alloy elements say carbon if you have carbon the eutectoid temperature is irrespective of percentage alloy. The carbon content you have the eutectoid temperature around 723. Let us say, but if you add alloy elements say like nickel or manganese then you will find it brings down the critical temperature.

So, these are called austenite stabilizer. So, these are the elements which try to bring down the temperature, in which the austenite temperature in which austenite is stable. Here, carbon also included as an austenite stabilizer primarily, because if you look at this phase diagram, you can see you increase carbon content that austenite is the temperature it goes on decreasing, but yes this part these are not important. Very few steels here I mean except for two steels, we really use this part of really use application wise bulk of these application will be in this region and therefore, for most cases what we can say that carbon is an austenite stabilizer within this limited range.

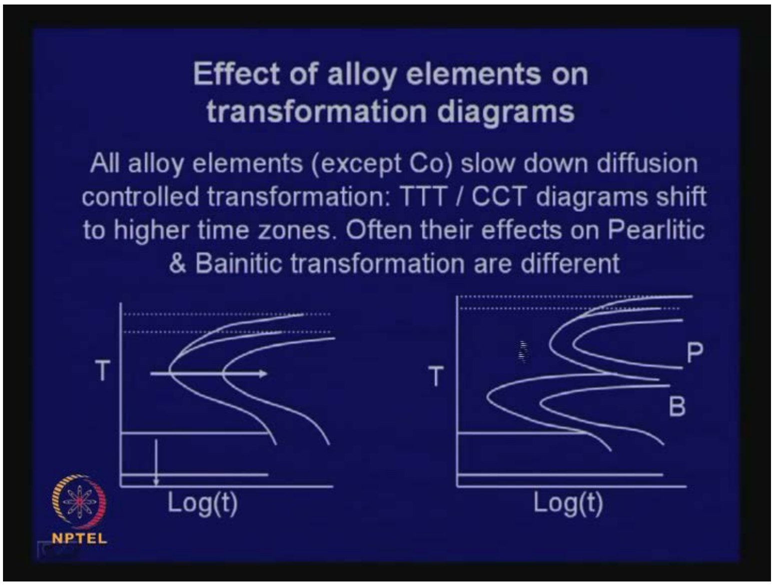
So, nitrogen also has as imilar effect and these all these alloy elements which are listed here and they make austenite stabilizer, infact there are certain grades where austenite can be made stable even at room temperature with relatively high amount of nickel or manganese. One very common austenite stainless steel you know many of you are familiar you find that this is primarily, because this has high amount of nickel and it is austenitic and austenite you know is an non magnetic. So, whenever normal you go and by stainless steel, you check with that with a magnet. So that says, either it has a high amount of nickel or manganese that makes the austenite, which is normally stable in plain carbon steel at very high temperature, they become stable even at room temperature.

So as against this, think about there are certain alloy elements and many of these will find, they will have a body centered cubic structure chromium, tungsten, moly. So, these are the elements where they are called ferrite stabilizer. They increases the temperature, they raise these critical temperatures like whatever is shown here. This eutectoid temperature goes up with the addition of titanium, molybdenum, tungsten, silicon, chromium and their relative power may be different, so primarily what is happening.

So, you have a broadly two classes available element, one is ferrite stabilizer which increases the critical temperature, another group called austenite stabilizer which brings down the critical temperature. Similarly, these alloy addition also alter the carbon content of that eutectoid structure, which is shown here percentage carbon in eutectoid steel.

Here if you add it, goes down irrespective of whether it is an austenite stabilizer or a ferrite stabilizer as you increase, these alloy elements eutectoid composition shifts, so that means if we look at these over here; so this point shifts to low carbon content, if you look at this sheet here this eutectoid point. If it shifts like this and so that means if you have this 0.5 carbon, you approximately say that here pro eutectoid ferrite amount is around 50 percent, but if it moves here what will happen, this amount of proeutectoid ferrite will decrease because pro eutectoid ferrite is proportional to this part. So, if this shifts here, amount of proeutectoid ferrite will be proportional to this over the total. Therefore, this will suppress presence of that means eutectoid percentage pearlite will increase with as you increase alloy element. So, this is one important point you must remember.

(Refer Slide Time: 38:58)

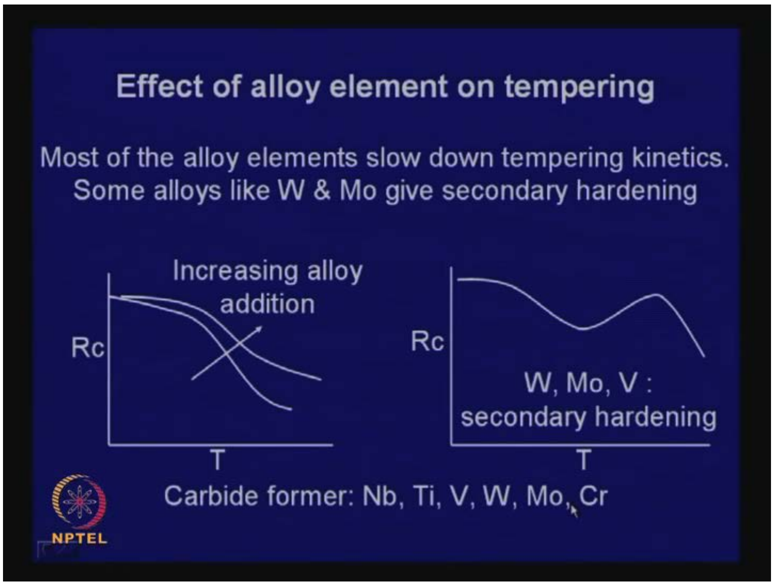


And then affect of alloy element also determine at affects these transformation kinetics like, both it affects both time temperature transformation diagram as well as CCT diagram. And in fact, this effect is shown over here all alloy elements except Cobolt slowdown diffusion control transformation. All alloy elements they slow down the diffusion control transformation and let us look at this diagram, see this TTT diagram is shifting to the right side. The n s temperature, the n f temperature they go down.

So, that means there is chance of having more amount of that retained austenite is increase -increases with in alloy steels. Similarly, that it is also possible that these alloy addition will affect both pearlitic and bainitic, this kind of eutectoid transformation high temperature, eutectoid low temperature, eutectoid transformation, pearlite is a high temperature eutectoid temperature, bainite is a low temperature eutectoid transformation and these are affected differently. Particularly let us say for with chromium, you know this slows down pearlitic transformation, but not bainitic.

So in this particular case, you get a separate type, you get another p s kind of a temperature. A temperature below which you get a like here is a pearlite, starts forming below this temperature. Similarly, you can think of a bainitestart temperature, below this temperature you expect bainite to form is othermaly, and also we mention that under a continous cooling, you do not get chance of getting bainite in plain carbon steel is remote, but in alloy steel even by continous cooling, you can get benitic strucuture.

(Refer Slide Time: 41:03)

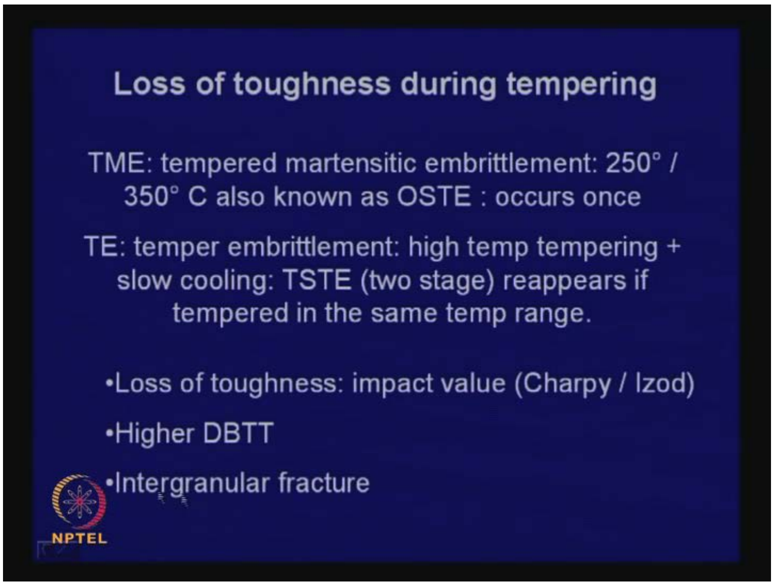


Now, this alloy addition also affects tempering process, we looked at the tempering process tempering is the diffusion control phenomena tempering is a diffusion control phenomena. And if you look at if you recollect the structure that we talked about and let us look at the screen that most alloy element will slow down the tempering kinetics, and some alloys like tungsten and moly also gives secondary hardening.

So, what happen this is the normal hardness versus a hardness as it drops, with increasing tempering temperature. This is the tempering temperature, this is the rock well hardness, this is ash quench hardness and with increase in time the temperature dropping, you have three distinct stages of tempering. This is the first stage of tempering, where you have high carbon martensite gets converted into low carbon martensite, with low c by a ratio plus possibly excellent carbide. Second stage where predominantly that reten austenite breaks down, and also this low carbon martensite also gets converted in to finally, into ferrite plus carbide and this epsilon carbide is also replaced by cementite and towards the end the cemetite starts growing.

So, that is why this hardness keeps dropping if you increase the alloy content, the rate at which these processes takes place that slows down they control diffusivity, because all these transformation is diffusion control. So, therefore they become slow; whereas if you have moly and when these kinds of alloy elements, which finds some gives some secondary hardening, they forms carbide which are coherent with the matrix. And this is some kind of precipitation hardening takes place here; in this stage, that is why the hardness goes up again, so this is called secondary hardening. And this alloys element depend they have different ability to be distributed either in the matrix or in the carbide, particularly these elements which are listed here niobium, titanium, vanadium, tungsten, moly, and chromium. They are most likely they are they will be present in carbide whereas, nickel will be likely to present in austenite or later on in ferrite.

(Refer Slide Time: 43:50)

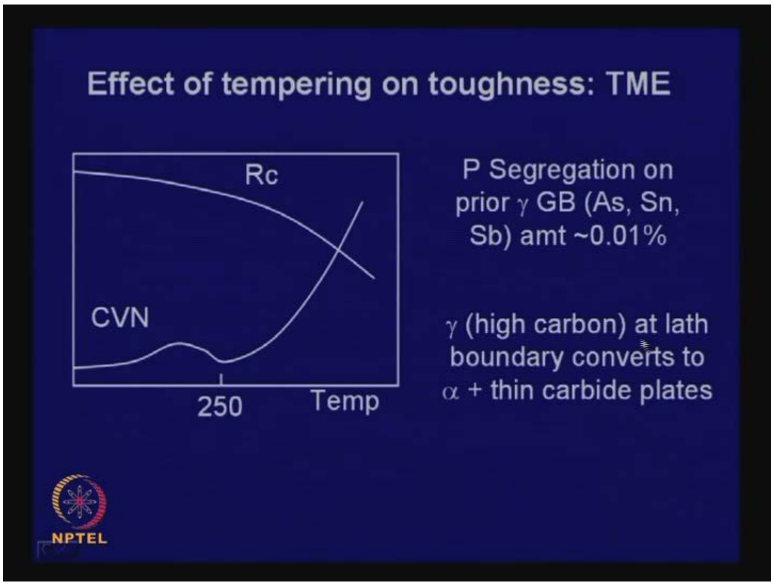


Now, during tempering often, we come across loss of toughness, and there are two kinds of which is called embrittlement, and this is also connected very well with alloy addition as well and there are two kinds of temper. One is called temper martensitic embrittlement, and this is takes place in these temperature ranges either at250 or 350, and these processes are also diffusion control. They are some kind of precipitation and this are also diffusion control process, and sometimes their kinetics is such that, this is fastest around 250, and with some alloy additions otherless, it can change to 350 and this type of embrittlement; is also known as one step temper embrittlement.

This occurs once only during tempering. There is another kind of temper embrittlement this is a relatively you get, if a material is steel is tempered at relatively high temperature around say, may be 600 degree centigrade and after that if you slow cool, you find there is a loss of toughness. This is called two stage and it reappears say suppose, if you quench, but again you heat it to the temperature range around say 500 degree centigrade it reappears, if temper in the same temperature range.

And, how do you detect this loss of toughness, so this is actually, this loss of toughness is the best way to measure is charpy impact value – charpy or Izod impact value, where you try to not specimen is fractured under a hammer as a pendulum, kind of an hammer and you try. And we talked about it in earlier classes and try to find out how much energy is absorbed by this notch specimen to fracture. And you will find that, once it becomes m brittle it has a very poor toughness, it is impact value is low. Martensite has such has low toughness, but as you start tempering its impact value starts increasing and suddenly if you come to this temperature ranges, again it starts decreasing it also has a higher ductile to brittle transition temperature and characteristic, you look at the fracture it will exhibit inter granular fracture.

(Refer Slide Time: 46:28)

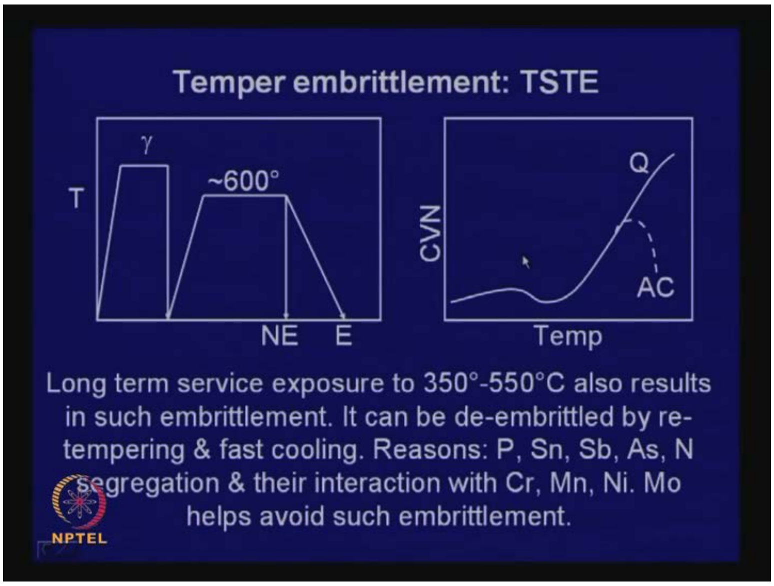


Now, effect of tempering on toughness say particularly, let us consider temper martensitic embrittlement; I said this is around this temperature range, it takes place around 250. And here the hardness, this is how the hardness is dropping from the hardness you cannot make out whether the material hardness this low hardness does not necessarily need high toughness. Look at here, the hardness has significantly dropped down, but again the toughness was beginning to increase with the temperature, but there is a drop over here thereafter this goes on increasing.

And this type of embrittlement is primarily associated with segregation like phosphorus segregation some of these and this segregate to prior austenite grain boundary. And some of the other segregating elements, these are not added intentionally, they come by chance and their amount is extremely small in the total alloy; but when the segregate the grain boundary concentration becomes extremely high and people have determined this by o j electron microscopic amount and it becomes substantial. They do not show up as precipitate, but the concentration is quite high at the grain boundary.

So therefore, if you have so the problem comes up if you have a fine grain, then you can say this the segregation chance will be less that amount whereas, if you have a coarse austenite grain, that is also an another reason the affect of this kind of embrittlement will be even more severe. To overcome this, you have a fine grain or fine prior austenite grain size and secondly try to control this tramp elements which are not which are not supposed to be there. Also people are thought about one is the segregation and another people think there are actually some amount of high carbon retain austenite. If you see the austenite, which forms towards the end, sometime they can have a high carbon content a lath boundaries, these retain austenite they have high carbon contents and these boundaries convert into ferrite plus thin carbide plates and this makes it brittle.

(Refer Slide Time: 48:56)

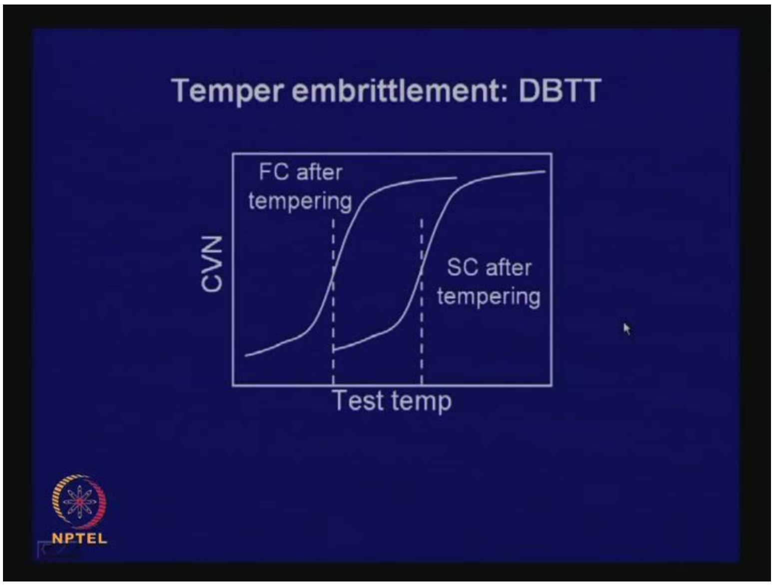


Now, temper embrittlement which is actually a two stage process so it is takes place as many times, you know heat it to the this acceptable temperature range and this is shown here. This is the normal hardening, you make it to austenite quench and then you temper it at600 degree centigrade and if you try to cool it, if you quench it after tempering then you find the toughness is high, but if you cool it slowly, then you find the toughness is low. And this is the plot which show the chorpyv notch values against tempering temperature. So, this is that 250 tempering; this does not make a second time temper, you do not get this is can be this is reversible occur again. So next is goes on and if you quench after this follows this path and in fact this quenched I mean after like 4340 steel which is a very popular steel and this is used as a spring, and many other very critical application ultra high strength steel.

This gives best combination of strength and toughness, if it is after hardening and subsequent tempering. If it is oil quenched, you get this but if you air cool, then such steels are prone to this kind of embrittlement. This embrittlement is also is primarily because of segregation of these elements and also their interaction with these alloy elements and this depend on the alloy element and out there is one element which is actually helps removes such kind of embrittlement.

And this steel can be de embrittle, and see if the steel can become embrittlet hen you can give asecond treatment, and after you oil quench it is no longer temper embrittlement, but you hit it again the temperature range 550 degree centigrade whole day you find it has become embrittle. And in fact that many of these power plant steels which are used in many cases harden and tempered condition, and they are kept for very long duration at around 550 degree centigrade, so they become quite. They are quite prone to such kind of embrittle the service type embrittle and here after this, if you remove a material if you give this kind of a heat treatment again you can restore the toughness.

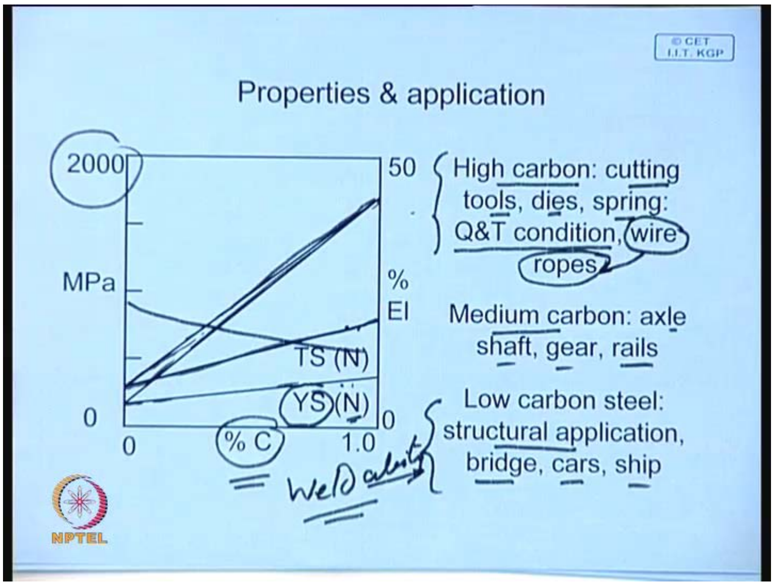
(Refer Slide Time: 51:51)



Temper embrittlement is also associated with increases ductile to brittle transition temperature. This is say, suppose steel which is susceptible to temper embrittlement; if you fast cool, if you quench after tempering and you determine that chorpyvnotch value at different test temperature, you get a plot like this and here this is the place, where you can see you can get a50 brittle, 50 percent ductile fracture. So, what you can see this is transition temperature below this ,you see the material is brittle, about this it is ductile and this transition temperature is low, if you cool slowly after tempering then you will find say for such steel, if you try to find out transition temperature say it is quite high.

So, many of the steel if they become brittle, it is quite risky how to handle. Say suppose turbine blades etc, which made of such material, harden and tempered steels and they are susceptible to such kind of temper embrittlement; in fact, you will find that the service expose material has become brittle. So therefore, you have to handle with here during any inspection, you should not hammer and cause crack to initiate and that can cause a severe problem. So, you have to be careful you must know the whether the steel is susceptible to such kind of embrittlement and take appropriate precautionary measure, when you are doing performing such any examination of any service exposed components.

(Refer Slide Time: 53:48)

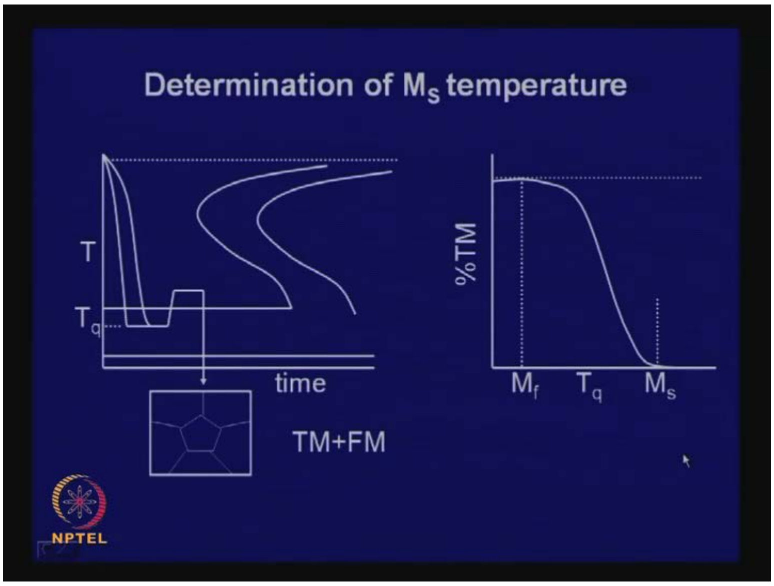


A quick look at some of this application properties, primarily let us look at we will take up alloys steel separately, and let us see that with plane carbon steel. This plot gives you properties that you can expect that you change from nearly 0 to 1 percent carbon, the strength it can increase significantly, and in fact you will find that if you normalize you get one kind let me try to find out the sheet.

So, all these strength you know if you say that, if you quench then with percentage carbon or if you have this can become very high tensile strength can be very high, depending on the carbon content, you can have a very high tensile strength. Whereas, elongation if you increase strength, this elongation will always you will find with carbon content elongation will go on decreasing, but strength will go on increasing. If you have and that strength will also depend on the type of heat treatment, that you gave say (( )) strength if you normalize, this is the plot it that follows. If it is a tensile strength, that you are measuring this is how it will follow, but if you harden then you can get substantially very high and in fact in harden steel you will find the difference between tensile and (( )) that also becomes smaller, but ductility and toughness will decrease with increase in percentage carbon content.

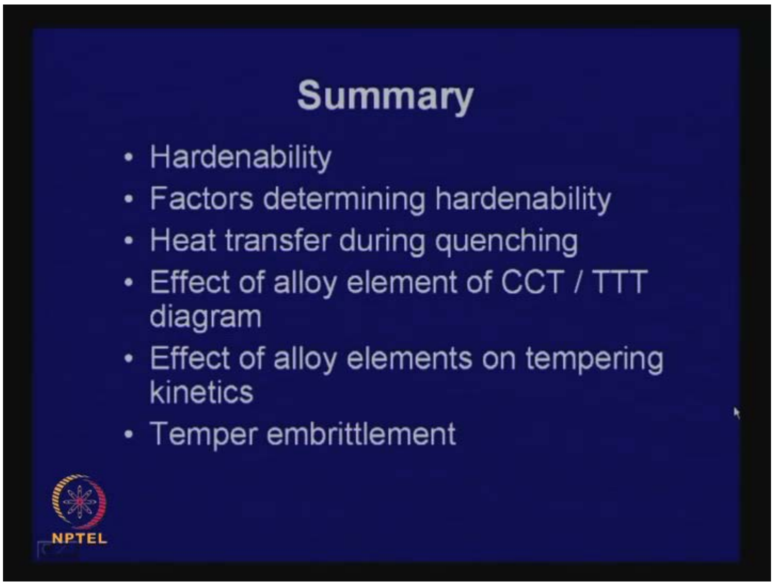
But hardened by after hardnening, if you temper you can improve ductility and toughness. To sum up, you see some applications, which are listed here; high carbon steel particular application cutting tools dies then spring they are used in quench and tempered conditions. We have wire ropes, these are also high carbon steel, but they are given a very special heat treatment we will learn about it little later. And here the strength can be (()) as around 2000 kind of MPa and they are used for wire ropes and load carrying even bridges etc rope bridges, where bridges are made of this type of steel. The medium carbon steels are used for rails, axles, shaft, gear then low carbon steel bulk of the material, belong to low carbon steel, they have bulk application is structural application brige, cars, ship and one of the important property; that they must have apart from this strength and ductility. They must have good we ldability should be they should be we ldable; whereas, these materials they will be extremely difficult to weld.

(Refer Slide Time: 57:22)



And I think a quick look as a determination of M s temperature one way can to take a sample quench, it below M s then quickly raise the temperature and then quench it and then look at the microstructure, certain martensite which forms here and get temper over here. And this tempered hardmartensite, when you develop microstructure will appear dark. Looking at this microstructure, you will be able to find out amount of tempered martensite and fresh martensite, and if you plot percentage of tempered martensite, you will find you get this type of plot.

(Refer Slide Time: 58:01)



So, with this we finish this topic on the heat treatment what we looked we have today we looked at hardenability, factors determining hardenability, we looked at heat transfer during quenching, looked at effect of alloy elements, we looked at alloy element effect on tempering kinetics, we looked at temper embrittlement and also determination of M s temperature. Thank you.