Principles of Physical Metallurgy

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Lecture No. # 33

Heat Treatment of Steel (Contd.)

Our lecture on heat treatment of steel, this is the third lecture. So far, what we have seen is. We we saw that several types of equipment can be given to steel, because of certain specific characteristics of iron carbon system.

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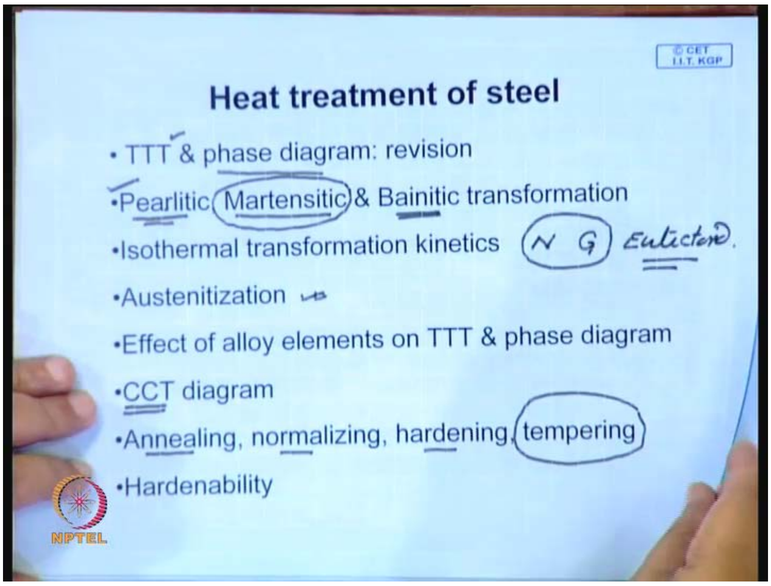

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Heat treatment of steel

- TTT & phase diagram: revision
- Pearlitic, Martensitic & Bainitic transformation
- Isothermal transformation kinetics (N G) Eutectoid.
- Austenitization
- Effect of alloy elements on TTT & phase diagram
- CCT diagram
- Annealing, normalizing, hardening, tempering
- Hardenability

And we looked at the time temperature transformation diagram so, phase diagram also has an important feature. And there are three distinct different types of reactions that take place, some are isothermal and some are thermal, like we talked to about pearlitic transformation, which is an isothermal transformation and other extreme we looked at martensitic transformation, which is athermal transformation. We also looked at isothermal transformation kinetics, which is actually a process where you have simultaneous nucleation and growth of the transformation product, we discuss this with respect to eutectoid steel, we eutectoid steel. But the process kinetics will be very much similar and in other case hypo or hyper eutectoid steel also we will look at what happens.

In all heat treatment process first stage will be austenitisation, we will also look at (()) this. And today we will also, there are certain characteristic of martensitic transformation which is worth recalling, these are the two extreme kind of transformation that takes place. Here, pearlitic transformation you have a very long range diffusion and this is controlled by nucleation and growth and other extreme case here, there is no diffusion and there is diffusion less transformation, we will see how does this take place a little more critically today. Whereas, bainitic transformation certain features which match with pearlitic, certain features morphology which matches with martensitic. So, I mean, but basically here some precipitation does take place so, bainitic transformation is a transformation where some amount of short range diffusion of carbon atom is essential that is the key.

And today we will also look at some of the common heat treatment, commercial heat treatment annealing, normalizing, hardening and we will also see all harden structures are given a subsequent heat treatment called tempering. And to know this commercial heat treatment, it is also necessary to know about a diagram called continuous cooling diagram, because most commercial heat treatment process you will not be, transformation will not take place at a constant temperature, we will be cooling the sample continuously.

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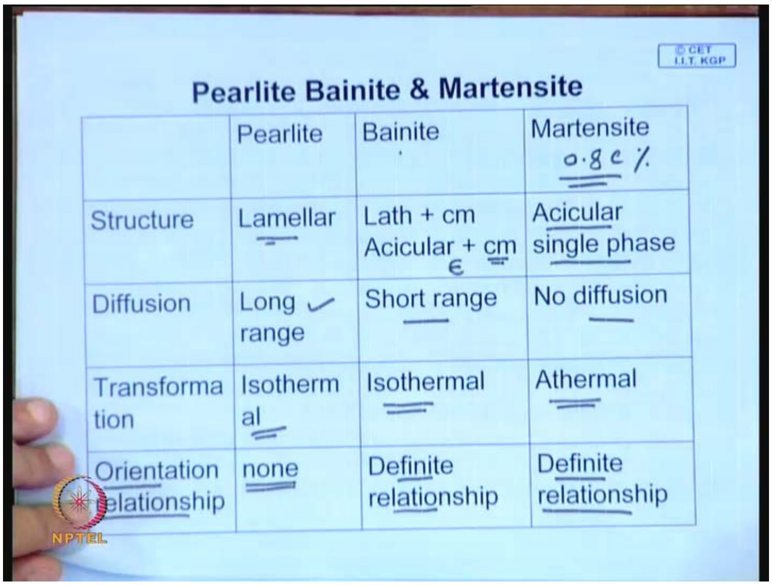

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Pearlite Bainite & Martensite

	Pearlite	Bainite	Martensite 0.8 C %
Structure	Lamellar	Lath + cm Acicular + cm ε	Acicular single phase
Diffusion	Long ✓ range	Short range	No diffusion
Transformation	Isothermal	Isothermal	Athermal
Orientation relationship	none	Definite relationship	Definite relationship

Now, let us quick recapitulation of the three different types of transformation which takes place pearlitic, benitic, martensitic, this we looked at, their structures, this is lamellars here, we have two variant lath plus cementites another lower temperature benite they are nearly acicular or plate type and where carbides may be cementites or in cases they can be epsilon carbite.

Here, we are considering say this is written specifically for 0.8% carbon steel, eutecoid steel, where the martensite will be acicular primarily acicular or plate type martensite, it is single phase whereas, in these cases they are two phase structure. So, this clearly shows that, there is no precipitation, no distinction. So, in this case as we mentioned long range diffusion, benite short range diffusion, here there is no diffusion, this is isothermal this is also isothermal. We can say this is a high temperature eutectoid reaction, this is you can say a little lower temperature eutectoid temperature, but this has also isothermal character whereas, martensite transformation is thermal.

Now, whenever transformation takes place the precipitation in certain cases they take place on particular plane, which is known as particular plane of the matrix and this is called orientation relationship, in case of pearlite cementite can form one, there is no definite relationship on which plane cementite will form, but in benite there are definite relationships, and in fact these relationships can vary with the morphology, lath will have one kind, acicular or plate type structure will have another kind. And similarly, martensite will also forms on definite crystallographic plane that, this also has a definite crystallographic relationships so, intermediate product benite has certain character which matches with martensite, certain character which matches with austenite.

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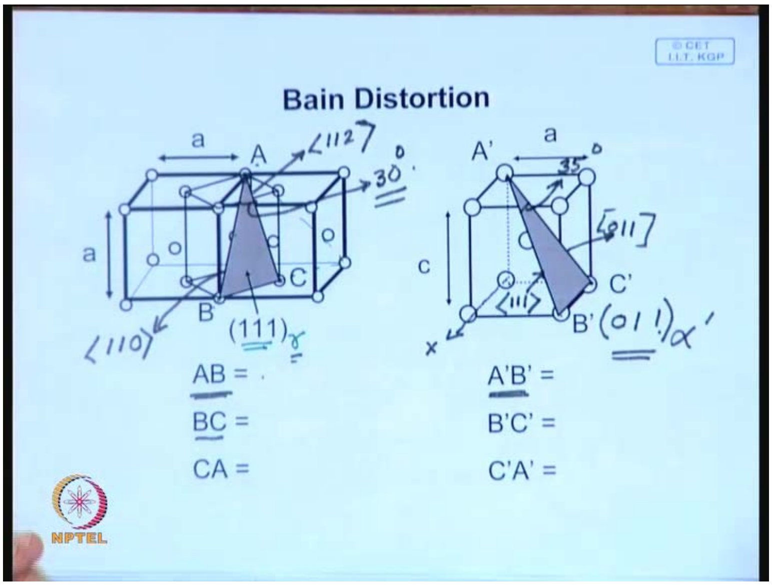

Bain Distortion

AB =

BC =

CA =

A'B' =

B'C' =

C'A' =

Now, last class we talked about how the deformation takes place in a martensitic transformation takes place, when you are quenching that, at the temperature form which you quench at that temperature structure of steel is austenite, which is phase centered cubic structure. And you have some carbon atom and number of carbon atoms say, even if you have one atomic percent find you so, there may be in unit cell or I mean may be a collection of unit cell, if you have fifty atoms that will be one atom of carbon. So, number of carbon atom with respect to iron is very less, and this side carbon atom occupies octahedral sides and which is shown over here say, look at this octahedral, these are two neighboring phase centered cubic cell which are shown over here, and these interstitial atoms they will be present at these octahedral sides so, this like this, one common octahedral side in the centre of the phase centered cubic structure so, these are the octahedral sides, but mainly only one in every fiftieth atom will be a carbon atom.

Now, whenever this atom is present, this distance is smaller compared to this distance so, in a b c c lattice you will find that, this distance in f c c symmetric it is same in all direction, that octahedral side. But when it transforms to a b c c it has to contract in this direction so, which is shown over here, if a is the lattice parameter of austenite which is of this order, this is the lattice parameter of austenite whereas, the lattice parameter of ferrite is around this. And look at this of very low carbon concentration (()) almost can be considered as a b c c, and look at a how a b c c structure can form over here. So, look at this cell which is drawn here, this particular cell, here you have a center atom here, you have a center atom which is iron atom so, this is an iron atom at the center of this lattice and, but this dimension if you look, this dimension is a whereas, a is the lattice parameter of austenite and whereas, this dimension which becomes one of the see, see either a or b of the b c t or the b c c lattice. So, this is actually a over root 2, this also is half the diagonal, this also is a, this as well as this. So therefore, the same (()) thing is drawn over here so, this is a over root 2 this is a so, this is not a b c c lattice, to make it b c c what you have to do, look at this, this is much larger than this dimension.

So, what you have to do? You have to compress it in this direction and a over root 2 is less than this value and you have to expand in this direction. So, you will have, to transform this unit cell to a martensite unit cell you have to keep this kind of deformation, 20% contraction along the z direction or along the c axis and it will expand 12% along this direction, along this direction expansion, and this directions you have to have contraction. And then you know this lattices, these the this becomes equal to this and this becomes equal to this nearly equal. If you have carbon atom will see later, there will be, this will be, if you have high amount of carbon then, this lattice get distorted it is body centered tetragonal, but which is very close to this c by a ratio, this axis becomes c and this will be close to I mean, not very much different from one, depending on carbon content it can be 1.05 or around something. which is actually very nearly you can say it is a b c c structure.

Now, if this type of transformation takes place then, there are certain crystallographic restrictions which must be followed. And look at this, this is shown in this next slide here, look at this this, this is the cell in the previous diagram which gets converted into a body centered structure now, look at the correspondences of different planes and directions in this case. Now, here try and find out, what is this plane? It intersects here at unit distance, here at unit distance, here of course, you can extend it here. So, this this plain if you extend it is something like this so, this plane which is known as, numbered as, a named as a b c, this plane is actually a 1 1 1 plane and this is a plane in austenite lattice. Now you look at this, when it becomes transformed into a martensite or b c t or a near near b c c structure so, this plane this a here is a prime, b here is b prime and c here is c prime. Now look at this and then you can easily see that, this plane now what is it seemly says? So, it is parallel, what you can see it is parallel to the x axis, it is parallel to, it intersects z axis at 1, this is it intersects this axis at at 1 so, it is a 0 1 1 type of plane in ferrite or martensite. So, that means this plane and this plane this plane and this plane they well have a close relationship, and in fact this is called the habit plane in one particular case we can say this plane is parallel to this plane of a cube, a particular this is octahedral plane 1 1 1 plane of austenite is equivalent to 0 1 1 plane in martensite. Similarly, their directions also, you can try and find out this direction so, look out this direction this will be a direction, I am not marking this sign which, you try and find out what will be the exact directions, but this will be a direction of 1 1 0 type whereas, this will be a direction you know, this two places say half unit along, say to reach from here to here you Move two units along z axis, half along y, half along x axis. So, this particular 1 is 1 1 2 type direction and if you try and find out this angle, this angle will come out to be around 30 degree.

Same thing you do over here, find out this so, this is, what is this? This is a two diagonally placed points are joined so, this is a 1 1 1 type directions whereas, this is a 1 1, say 0 1 1 direction so, if you find out the angle between these two it may not be exactly this, but it is within close so, this we may find this is around 35 degree. So, crystallography these planes are almost similar and I leave you as an exercise for you to find out these indices so, this direction in this austenite will be parallel to this direction in martensite, now the question comes is, how does this kind of homogeneous bain distortion can take place in a lattice? So, bain distortion is a homogeneous distortion, what you are trying to do? You compress the lattice in the c axis expand in say z axis, you are compressing, you are expanding pulling it along x axis, pulling it along y axis. So, this is a homogeneous deformation and in this case, are there any undistorted plane? Or undistorted directions?

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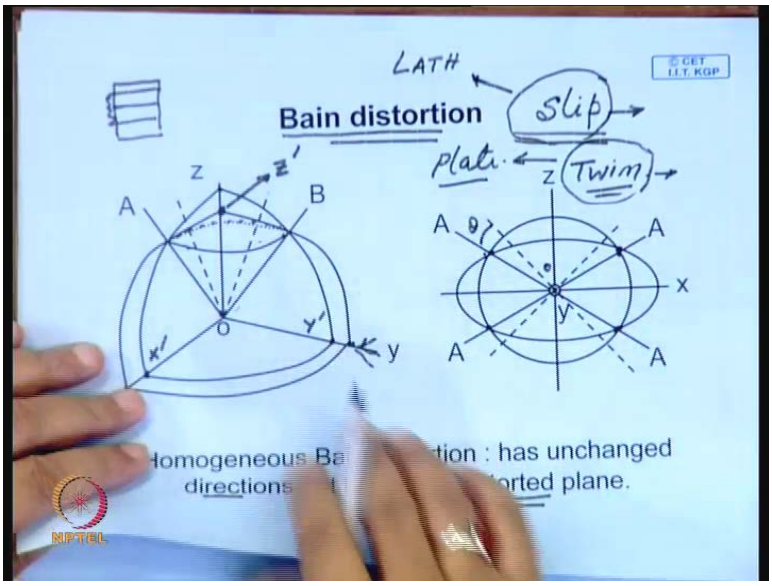

And to understand this, if you look up I mean, try and construct in 3 d on isometric view, this is x y z axis and you have considered a sphere so, this is one eight part of a sphere which is. And now, suppose you are compressing this sphere along z direction so, it from here it comes to this point this is at a z star similarly, x you compress here so, it goes x star, y you compress from here to here it becomes y star so, now you construct this surface. What do you find these two surface they will meet along this curve so, this is at plane on which it (( )) so, any direction on this cone say like o is the origin o a, o b, or any lines here which is line on the cone, these directions are unchanged directions. But here you know, whenever a slip process takes place or or certain deformation processes takes place, certain plane remains unchanged, like in case of a slip, when a slip is taking place the slip plane remains undistorted lattice around that gets distorted, but that slip plane remains undistorted similarly, when (( )) takes place a part of this above the twin plane is just slightly gets tilted so that, this becomes a mirror image, that part top part becomes a mirror image of the bottom part so, this is the kind. So, here also you will find the twin plane, any direction line that you draw along twin plane is undistorted, but other any thing that is perpendicular or other directions they rotate. So, the same thing what you find over here, when you have a homogeneous deformation you have only certain undistorted directions, you cannot think about a an undistorted plane.

Now in order that, say suppose this bain distortions so, that bain distortions is a serial distortion, how will this be accommodated in the lattice? So, we know the crystals can undergo if you have apply too much, if there is a too much of distortion or too high a stress the material deforms, its shape changes either through slip or through twin. Now, the question comes is there a possibility say suppose, look at the same thing this is here we have drawn a projection, projection look from looking from this direction, you look at it from this particular along the y axis, in that case this is the sphere which is undistorted now you have compressed it along and in that case that y point will be projected at the center, this is the origin also and y will be located at the origin here.

Now imagine that, this has compressed along this direction and x direction it has expanded similarly, and the y which is perpendicular to this plane here also there is an expansion. Now look at this, here these directions these points these points of intersections. Any line passing through actually, this will be form in a 3 d it will be a cone and anything which is passing through this point that cone so, these are undistorted directions. But you cannot think about an undistorted plane, to get an undistorted plane, what you have to do? You have to find, say suppose one of the y plane which intersects here, say this is y is perpendicular like this so, any plane which is passing through this suppose, you rotate it through an angle theta then, it will match with this so, that means you can think about an undistorted plane provided you allow certain amount of rotation in the crystal lattice.

So, that means to accommodate bain strain so, that means it is in the crystal lattice you have to visualize some kind of rotation of the part of a crystal in the lattice so, what it means? The homogeneous bain distortion, this has unchanged directions, but has no undistorted plane and therefore, to accommodate that kind of a deformation will be extremely difficult so, the crystal will deform and this deformation can be, through that it can relaxe the stresses and this is possible through two processes. One is slip, and we have seen earlier slip is a simple ((shiar)) process so, it is actually which is made up of there is a some amount of rotation involved another is twim. Now, slip can take place through this rotation right whereas, twinning you know some kind of a lattice rotation now, in this case slip you have say several planes you know, if you have a slip plane say this is one plane you can think of several packets so, each can slip like this say this so, these bands the slip over here whereas, in case of twim the atom moves the fraction of an atomic distance and on each plane the atom moves the same distance so, that is twinning. So, through this it is possible to accommodate bain distortion in the crystal lattice and with this it is possible to explain actually, through slip it is possible to explain one kind of a that crystallographic relationship it is possible to explain, because deformation the slip can occur on specific planes, say like slip plane in a phase centered cubic it is 1 1 1, b c c the slip can occur on 1 1 0 plane. So, that way I mean that, there are certain so the which can explain that crystallography transformation and depending on which method, Whether the bain distortion is accommodated by slip or twim, we have two different kinds of a martensitic structure this gives represent name is a lath martensite whereas, this gives plate type of martensite or acicular martensite.

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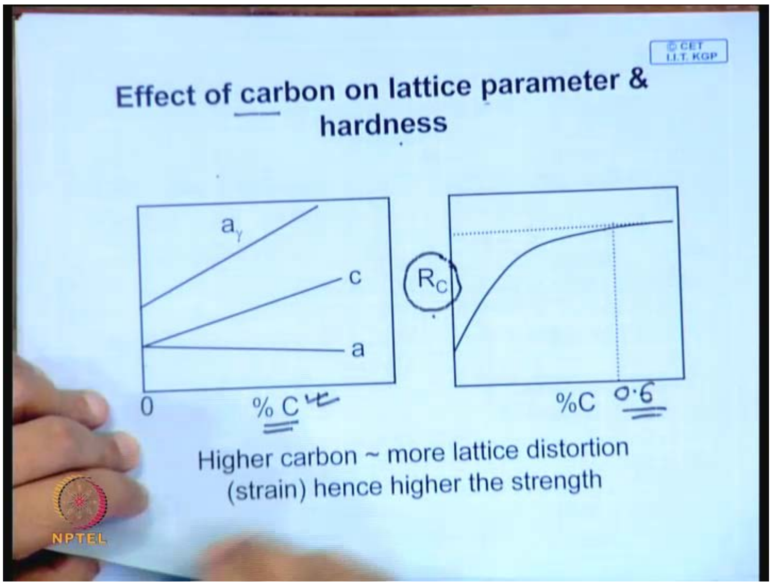

Effect of carbon on lattice parameter & hardness

Higher carbon ~ more lattice distortion (strain) hence higher the strength

Now, crystal structure of course, is a function of carbon content which is shown over here, what is the effect of carbon content on lattice parameter and hardness martensite. Now, look at this if it is austenite lattice parameter increases almost linearly with carbon content whereas, if you increase the carbon content in say in martensite you will find c axis increases with carbon content whereas, a decreases decreasing with carbon content so, on the whole it is the c by a ratio which increases with carbon content.

So, higher carbon content is the more lattice distortion so, more local strain therefore, they have higher strength, apart from the solid solution contribution of carbon. So, martensite what you have is a deformed structure, highly deformed structure either plastically deformed or a twim structure, and which is sub microscopic it is very extremely difficult to see the plates are the that fine structure of the plates or the laths you can see only under transmission electron microscope. And the dimension of the lath etcetera, the lathe or plate that interpolate spacing they are of nano meter dimension say, it is say distance may be several atomic layer say eight to ten atomic layer.

So it is actually a nano structure, now fine structure is a nano structure can be seen only under electron microscope and such fine structure definitely asho/associated associated with increase hardness which reflex over here, and if you measure the hardness like this for different carbon containing martensite you will find there is a relationship of hardness measured on the rockwell scale follows a plot like this. And somewhere around 0.6% carbon it almost that increases not significant, but nevertheless rockwell scale is not linear so, may be you measure in weaker scale you will find that even beyond 0.6 the hardness of martensite can increase.

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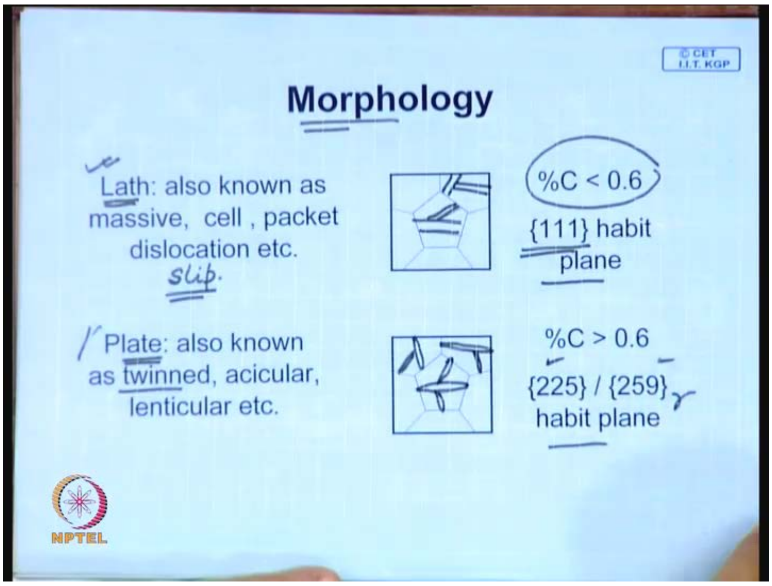
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Morphology

Lath: also known as massive, cell, packet dislocation etc.
slip.

%C < 0.6
{111} habit plane

Plate: also known as twinned, acicular, lenticular etc.

%C > 0.6
{225} / {259}γ habit plane

Now a quick look, we looked at the martensitic transformation in little detail about the crystallography which has an effect on morphology, which is shown as, see one class is lathe which forms because of dislocation movement or through slip, slip is the main mechanism and these are slip bands what you can see here, these are slip bands which you can see, it is an exaggerated view you can see this fine structures within this lath only on electron microscope. So, these are the kinds of structure and it has a rational I mean habit plane, and this type of structures forms a low carbon, relatively low carbon steel. And this is, present name is na/lath lath, but it has been known by several other names earlier also which is shown here. And other one that where you have in rational plane it is a needle like structure, and this is the structure, and in this case this interface movement whether it is lathe or whether it is plate type martensite, this is very fast this moves almost at the speed of sound therefore, if in theories it should emit or it should emit acoustic noise and which can be audile and I mean, which is in the audible range. And which is in fact of course, it is masked by certain other signals, particularly since you are quenching there will be certain other noises also, but it is possible to filter out these noises and also monitor the noise that comes out from the formation of this martensite plates or laths.

And in this particular case, if you have a twinned martensite, which is formerly known as plate type here the habit planes are irrational, it can be either this or this of forms on these planes of austenite.

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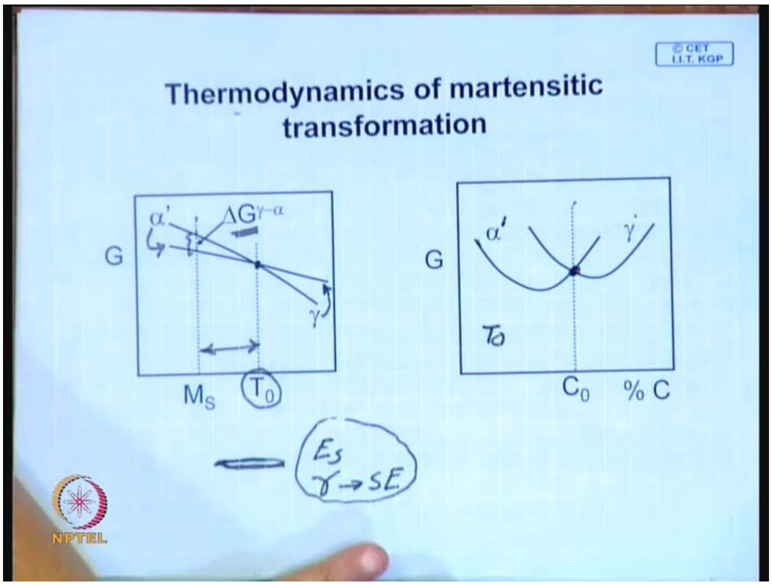

Thermodynamics of martensitic transformation

Now, when such fine structure forms often it may be I mean, we are applied the principle of thermodynamics and this has been applied to martensitic transformation as well, and we know the two phases say high temperature phases austenite, if you plot the free energy of austenite which is shown over here, free energy of austenite and free energy of ferrite so, this is ferrite free energy of austenite.

So, above a particular high temperature austenite is more stable as you pull down somewhere it mean austenite and martensite may be both may have same free energy, this temperature is known as t 0, and m s temperature is shown here. And two things are happening, when a martensite needle of a plate forms which is asho/associated associated with high amount of strain so, it has a lot of strain energy apart from this interface, apart from interface energy that is surface energy you have a significant strain energy, which will oppose the deformation so, these are positive contributions whereas, (()) that means what you need for martensic transformation to take place? You need certain amount of super cooling, and this is the amount super cooling.

And when you have a certain amount of driving force, this is the free energy for driving force for martensitic reaction. If you look at the free energy composition diagram here also which is shown, this is the free energy composition diagram of martensite, this is the free energy composition diagram of austenite at a particular temperature, let us say this temperature is t 0. Here, say look at this for this particular composition c 0 is the composition here, if you cool you know it is possible to suppress precipitations, but this does not happens at this particular temperature, you have to under cool and you can use your principles of..

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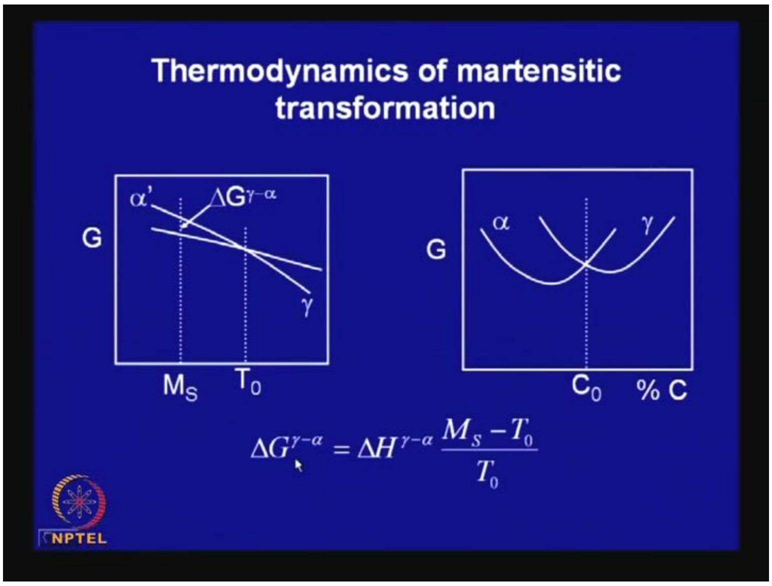

Thermodynamics of martensitic transformation

$$\Delta G^{\gamma-\alpha} = \Delta H^{\gamma-\alpha}\frac{M_S - T_0}{T_0}$$

What you can do is, it is possible to calculate this driving force in the same way we walked out for precipitation process, this is the under cooling so, this driving force is proportional to the under cooling higher the under cooling, higher is the driving force for martensite formation.

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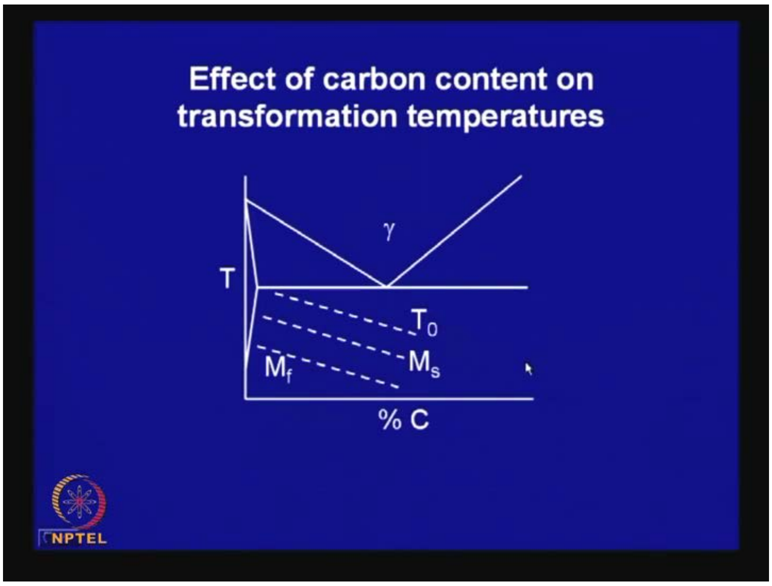

Effect of carbon content on transformation temperatures

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And it is possible to draw the super imposed from the iron carbon phase diagram, this particular relevant portion of the iron carbon phase diagram the temperature t 0. So, this is a function of carbon content, higher the carbon content t 0 is lower so, also m s or m f. So, that means m s, m f temperature should also be function of carbon content or composition of the steel.

Higher the carbon content lower is the m s, lower is the martensitic temperature- m f temperature completion, finish temperature and lower is the t 0 that is equilibrium temperature.

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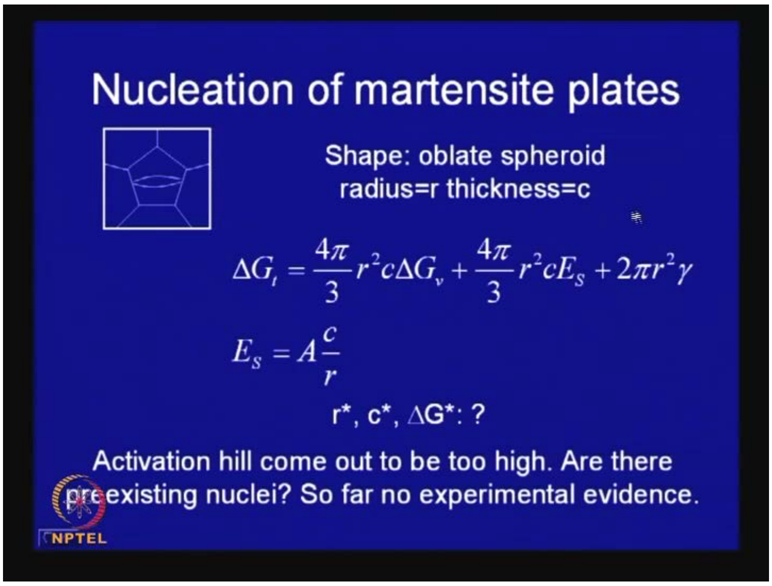

Nucleation of martensite plates

Shape: oblate spheroid
radius=r thickness=c

$$\Delta G_t = \frac{4\pi}{3} r^2 c \Delta G_v + \frac{4\pi}{3} r^2 c E_S + 2\pi r^2 \gamma$$

$$E_S = A\frac{c}{r}$$

r*, c*, ΔG*: ?

Activation hill come out to be too high. Are there preexisting nuclei? So far no experimental evidence.

Now, here if you try and apply exactly the same way, that concept of that nucleation process to get say you can ashume/assume assume the shape of this nuclei to be an nucleus of an martensite plate to be an oblate spheroid, it has an radius say radius is r and thickness is c.

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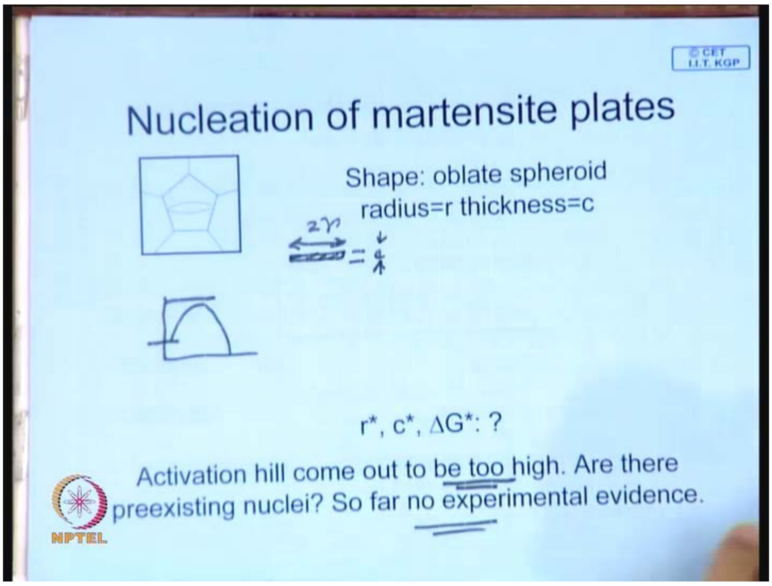

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Nucleation of martensite plates

Shape: oblate spheroid
radius=r thickness=c

r*, c*, ΔG*: ?

Activation hill come out to be too high. Are there preexisting nuclei? So far no experimental evidence.

So, something you can think about a thin plate, something like this the thin plate so, this radius this is twice r and plate thickness is c, this is the plate thickness. So, it is possible you can calculate its volume, you can you can calculate its surface area with this assumptions and which is shown over here.

So, suppose in this particular structure austenite this is austenite grain, if a plate of martensite forms like this and shape being oblate spheroid, it is possible to calculate its volume which is shown over here multiplied by the driving force v energy that, which is a function of under cooling then, there will be a strain energy asho associated with it, this will be positive so, this will be volume multiplied by that strain energy and usually the strain energy is a function of the shape shape of this plate so, how much is c over r ratio so, this strain energy is equal to a is a constant times c over r, plate thickness over the ratio over the radius. And then, this is you have this new surface being created so, pi r square is the top surface, pi r square is the bottom surface, to two things surfaces have been created times the gamma which is the surface free energy. So, if you write and then you go through the similar procedure procedure procedure it is possible to calculate the critical size of r star, critical size of c star, as also that activation hill now, if you find in this here, if you substitute the value, I will leave this to you to derive this expression and if you find this out there will be an activation hill. So, you have an activation hill which must be overcome for that martensite transformation to take place.

And people have calculated this activation hill comes out to be too high. So, then the doubt arises that, are there is nucleation is important, how does nucleation takes place if the activation hill is so high so, some people thought this possibly these nuclei are pre existing and only when that, what is it is growth control and when that growth is very fast, but nobody has seen today, even it is extremely difficult to prove also experimentally, there is no experimental evidence of pre existing martensite nucleus.

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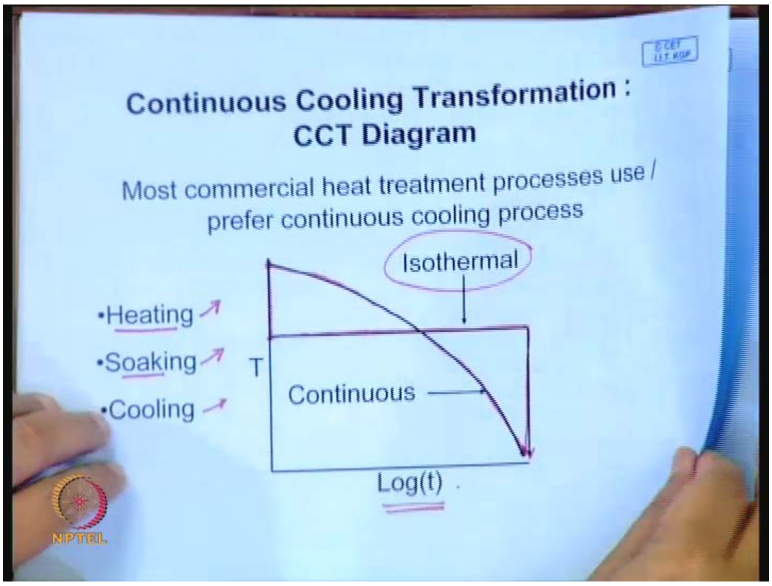

Continuous Cooling Transformation : CCT Diagram

Most commercial heat treatment processes use / prefer continuous cooling process

- Heating
- Soaking
- Cooling

So, with this little background on the nature of the deformations that can take place in iron carbon system, it is possible to understand what structural changes that take place in some of the common equipments which are given to steel, and mind you these equipments, people knew about it much before our understanding that micro mechanisms that, microstructural changes that take place, much before that all these were known and these people learn by experience. And in this case the cooling rate that one adopt is not isothermal cooling, in most cases we will heat it to a particular temperature and then either you quench in a medium so water or you let it cool in, take out the sample keep it in air in that case the sample cools in air.

So, that means the temperature of the job that, to which is being given the heat treatment changes continuously and how do you interpret the transformation that will take place during such continous cooling? And this can be infered from the isothermal transformation diagram, let us see how this is done. So, most this commercial heating this heat treatment processes, there will be three distinct steps so, one is you heat to a particular temperature and then you keep the sample for a certain length of time so that, it develops a homogeneous structure and then you so, that is called as so, that is (( )) called as soaking and after it is shoaked soaked you know you are sure the structure is homogeneous then, you are cool this is the third stage.

So, these are the three steps on any heat treatment process, and this cooling can be done in two ways, we talked about this isothermal cooling so, here this is the temperature where sample is heated then you quench it in a bath maintain a temperature t, and then you keep it for sufficient length of time for the transformation to be completed, and then it does not matter whether you fill slowly or fast the structure does not change, this is one kind of a isothermal transformation. Now, normally if you take out a sample and leave it in air so, it will cool something like this and usually this temperatures are plotted against logarithm of time, because time scale can be quite large, to represent the way the temperature decreases often we use logarithmic scale. So, in that case a constant cooling rate will be, will appear like this.

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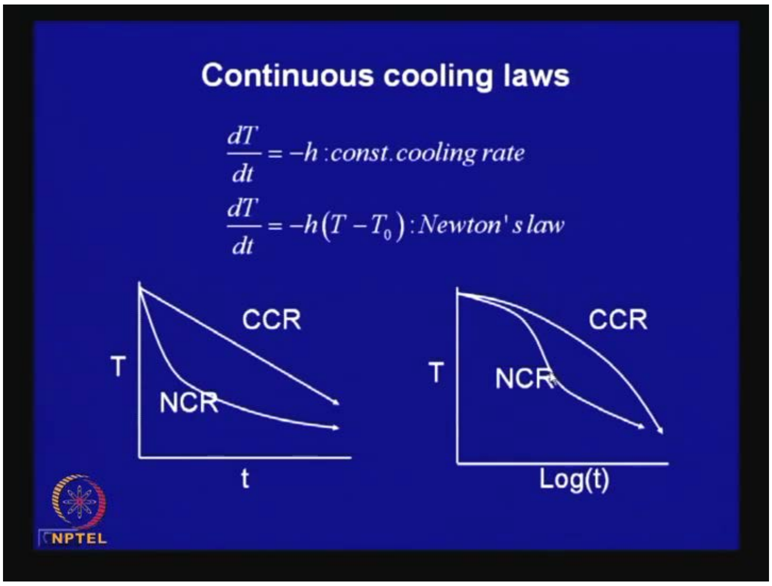

Continuous cooling laws

$$\frac{dT}{dt} = -h : const.\, cooling\, rate$$

$$\frac{dT}{dt} = -h\left(T - T_0\right) : Newton's\, law$$

And in fact, this is shown a little more critically here so, one can look at what are the continuous cooling laws. So, we can think of two type of cooling laws, see one is it could be say cooling rate is uniform another is that is natural cooling that takes place, when you take out you know, that any metal take out any particular temperature take it out keep it here let it cool.

So, in that case initially the cooling rate will be fast and later on as it cools down cooling rate becomes slow, as the temperature of the job decreases cooling rate decreases, and which is actually, mathematically, it is represented like this. So, one way could be a constant cooling rate here either you have to mechanize a device so that, the heat transfer rate is constant and you can maintain the constant cooling rate otherwise, if you allow it to cool naturally in all probability it will follow this kind of a cooling kinetics, this is the, that is decrease in temperature will be proportional to the temperature difference, this is the surface temperature, this is the surrounding temperature and heat flow within the job will be follow will follow the normal conduction (( )).

So, let us not go into the details of this on to sum up what we can see that, if you plot this cooling rate, if you plot this temperature against time then, this is the constant cooling rate, this is the newton or natural cooling rate, normal that is with the decrease in temperature cooling rate goes on decreasing. But if you super impose this on a temperature gives log t the shape of the curve may look like this.

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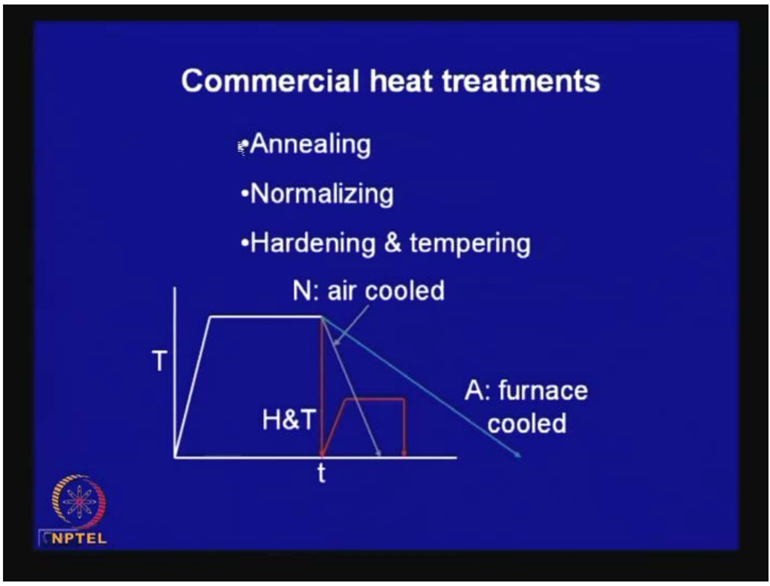

Commercial heat treatments

- Annealing
- Normalizing
- Hardening & tempering

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Now, let us try and find out, how, what are the common first, let us see what are the common heat treatment we are going to look at. Now, three common commercial heat treatment processes are listed here, one is annealing, second is normalizing, third is hardening and we will see when you harden since when martensite forms the surrounding lattice will undergo tremendous amount of strain and which is accommodated through slip or (( )). So, this introduces lot of strain and therefore, the structure is highly unstable and often it is susceptible to tracking so, it is given a treatment called tempering. And here, the heating cycles where, which is shown here say normal common is you heat it to a austenising temperature and you keep it, and this let us say first we are let us consider eutectoid steel. So, heat treatment temperature that austenising temperature irrespective of whether it is annealing, normalizing or hardening the temperature is around thirty to forty degree centigrade above the eutectoid temperature.

And here, this is the shoaking time, this is heating cycle, this is the soaking cycle after the structure has become homogeneous, the temperature is also uniform then, one way you can cool it extreme to quench in water, very high rate of cooling then, this is the treatment called hardening and after hardening it is given a tempering heat treatment, where you raise the temperature to a level some say hundred degree, hundred fifty or three fifty, but certainly much lower than the eutectoid, at that temperature some amount of transformation takes place some amount of ductility is restored brittleness goes down and then you can quench, this part is called tempering, and this quenching is the hardening, this red line represents hardening and temper.

Another case, which is where you take out the sample and just leave it in here, and if the sample allow it to cool in the air, still air so, this is the cooling rate say we assume that we are plotting is the state line thinking that we are able to maintain it, which is never, see, even if it is the cooling this does not matter so, this case what we say, is it is relatively much slower cooling than the cooling rate that adopting ductile hardening. So, this is called normailizing and extreme slow cooling, what you can do after soaking you can just switch off the furnace and let the job cooling the furnace.

So, in that case furnace cooling you get this type of heat treatment, where you the job is cool in the furnace which is called annealing. So, obviously you can see so, this is the case of hardening you get maximum hardness and air cooling the type of structure you get an intermediate structure, and here you will get the courses structure which will have the lowest (( )), but good ductility. So, as you go down you can see from annealing normalizing to hardening, strength goes on increasing whereas, the ductility goes on decreasing.

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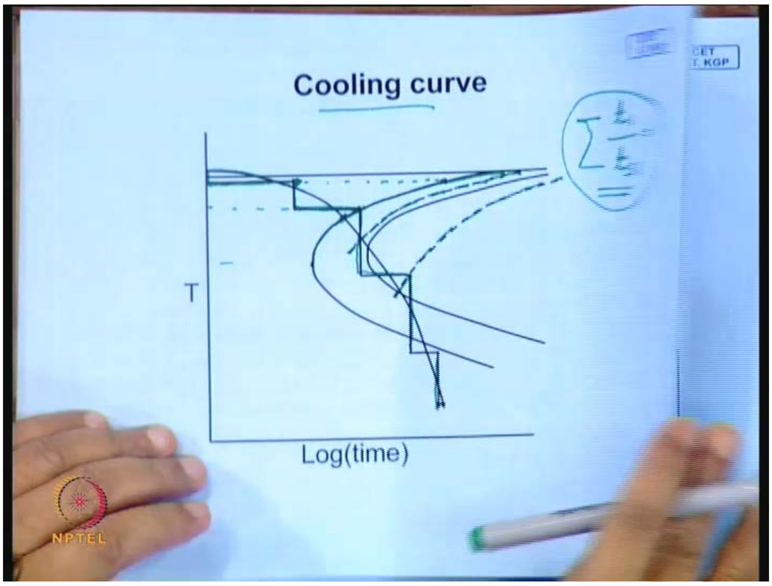
Cooling curve

Now, a quick look that how you can draw the cooling or infer the cooling c c t diagram from isothermal transformation diagram. So, here you see this is here we have an isothermal diagram which is super imposed and let us consider there for eutectoid steel, now in this case we can always think of that isothermal cooling you know, this continuous cooling, this is the continuous cooling path, we can always break it up into steps like this. I have drawn a very coarse step which can be made even finer now what happens you know, when you are cooling say suppose, as you cool it say if your cooling if this is the whole time so, here the whole time at a particular temperature quite easy to find out and what you can do if you look at this is whole time here, and here this is the transformation.

So it actually it remains for a certain fraction of the time so, a part of this transformation has taken place which is not visible, but that whole time is proportional to a part of this whole time, if you would have kept it that long transformation would have started, but you have not kept it that long so, a part and if we say that is cumulative here this fraction say we say that, this is t s 1 and we kept it at time t 1 so, this is the fraction of time it had spent here Similarly, when it comes here it remains for this so, here your total time is this so, what you can think about it can sum up so, here the total time over this, this is the time fraction which (( )) at particular temperature.

So, what you can spilt this up into this time and try and find out when this reaches 1, this is how it is possible to convert this isothermal diagram to a continuous cooling diagram, and obviously what it comes it obvious that, during continuous cooling transformation will not take place once this line intersects this, you have to cool it still further so, which is shown. So, this is the start of transformation in continuous cooling and similarly, there we are finishing

So therefore, this c c t diagram will be this part of the diagram, continuous cooling diagram will be entirely different and we will, it is also extremely difficult that benefic transformation does not taking place unless in plain carbon steel, unless you cool it isothermally below the nose so, this is the problem therefore, in most plain carbon steel diagram the c c t diagram if you look at you will find the diagrams are like this.

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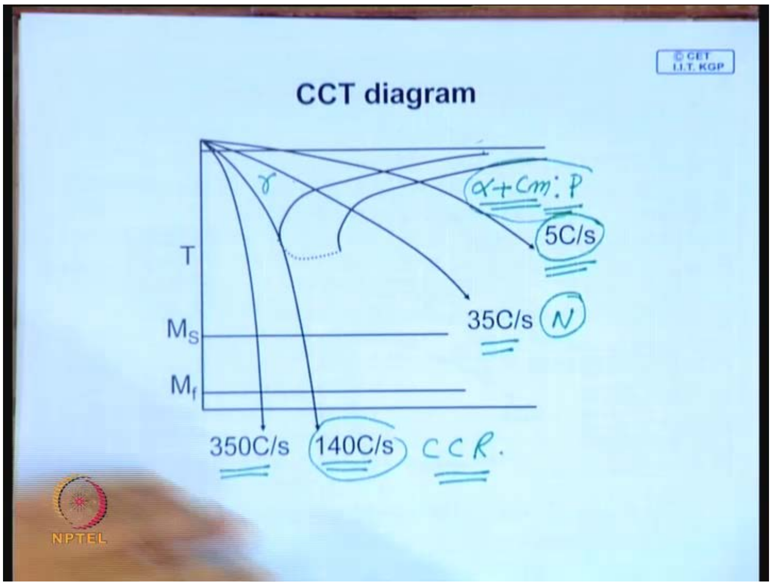

CCT diagram

So, only the pearlite portion, this is the austenite, here you have ferrite plus cementite, lamilar structure called pearlite. So, upper end you have course pearlite, below you have fine pearlite, and on this of super imposed just schematically different types of cooling rate that you can think about if you water quench that cooling rate is very fast, depending on whether you are quenching on water still, water or agitated I mean, the bath is agitated you can get a substantially a very high cooling rate, you can get a this kind of cooling rate and this is the critical cooling rate, if you cool faster than then/this this you can suppress diffusion control transformation, you can suppress pearlite transformation so, this is the critical cooling rate. And this is the average that normalizing, when you do air cooling then your cooling is follows like this, mind you this rates are approximate this rates will also depend on the dimension of or the size of the job that you have. And in case of annhealing when you do a furnace cooling, the cooling rate is as low as even lower as 5 degree centigrade per second.

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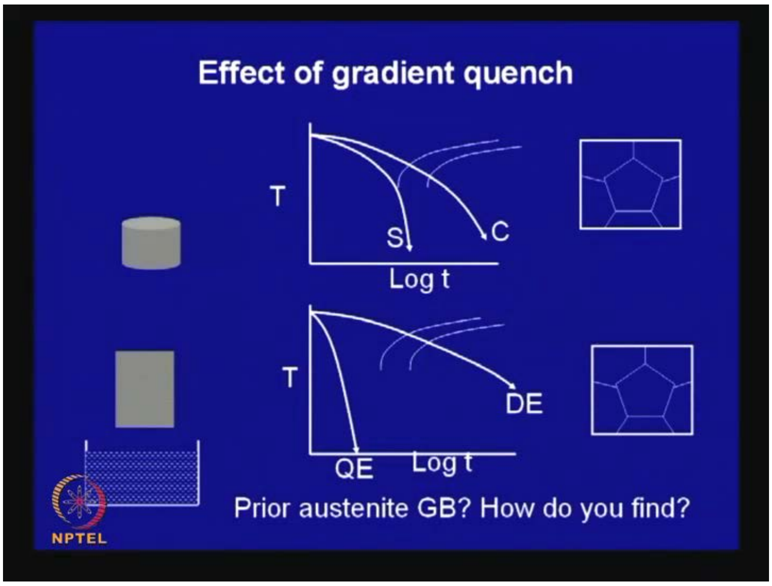

Effect of gradient quench

Prior austenite GB? How do you find?

So therefore, what you can infer now, what will be the microstructures or how will this microstructures look like or normally when you cool a job it is quite interesting it is if your job has a dimension, when you cool it is always not possible that every point will cool at the same rate, possibly you will find even if you quench a job in water the surface will cool very fast whereas, the center, the cooling will be controlled you know the way heat can be extracted from the surface as well as through conduction in the job, which will therefore, depend on the size of the job.

So therefore, what we can get is a possible a gradation of different types of structure you will get as different place, and which is pictorially shown over here suppose, this is a job you heat it is a red hot and now you quench it in water, if you put it in water you will find that the surfaces that cool down fast, but center is still hot, the stop surface is exposed so which is also red hot the side cool therefore, what you will have, you will have after that you take out, take a section and try to look at the microstructure, what you will find?

The centre surface will cool very fast, it is possible the surface will get the cooling like this which avoid the (( )) of the curve whereas, say which is shown over here the surface, this is the nose it avoids nose so, surface you will have martensite, but in between what will happen there can be some (( )) at the center which will be totally pearlitic, surface will be totally totally martensitic, and in between you can think about certain cases where you will have pearlite forming that is; pearlite which are formed, which are modules of pearlite, which are made up of, they will start with they will all form along the grin boundary, along this triple points so, they will get nicely marked. So, if you take out this this is the job, if you take a section look at the microstructure from surface to the centre you will get the microstructure will change, on the surface you will have martensite, on the center you will have totally pearlite and in between somewhere, you will find the structure like this. So, which marks the (( )) the prior austenite grin boundary in between after this, this portion martensite. And normally when you develop microstructure martensite is very difficult to use so, these will appear bright whereas, the pearlite modules they will be so fine they will appear as dark modules.

So, these modules mark these grain boundaries so, what it shows the austenite grain boundaries, the prior austenite grain boundaries you can find out by such a variant quenching technique or this type or any heat treatment process it is possible, to take a section it is possible to find out austenite grain size, if look at it you can also think of a radiant quenching say suppose, if you heat a sample like this and quench only one end like this, and when it comes out you take a section here also you will exactly get the similar structure, possibly here you may get modifying this, you may get a much quench end this is your cooling rate whereas, the other end this content you have a this cooling rate.

So, this is the way you can revise an experiment and this size of this prior austenite grain size is quite important in any commercial heat treatment process, as as we will see if the grain size is very course in that case we will get coarse austenite plates, also you will get martensite, also coarse martensite plates and when you quench you know this structure is often brittle and in fact you have to design your heat treatment process in such a way that, martensite develops in a relatively fine grains austenite structure in that case quench first susceptibility (( )) will be less.

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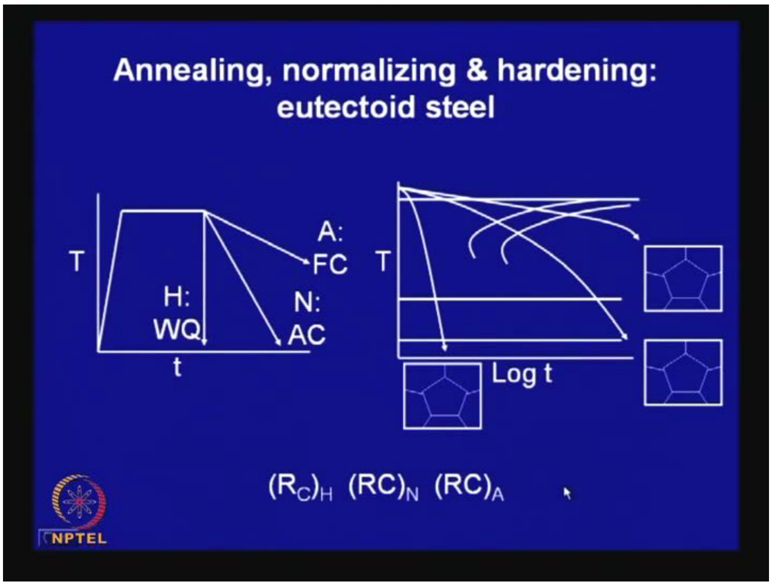
Annealing, normalizing & hardening: eutectoid steel

$(R_C)_H$ $(RC)_N$ $(RC)_A$

So therefore, what it means the size of this austenite grains can be controlled by controlling the austenisation process and in fact this is quite, in fact the first stage of any heat treatment is the process of austenisation, which is shown here, this is all austenisation, annhealing, normalizing and hardening of an heat it to the eutectoid temperatures, cool differently and these are the structures, and I will leave it to you to draw the microstructures, here it will be annealing pearlite, here it will be fine pearlite and in case of a hardening it will be martensitic structure, and this will be the hardest it will be the maximum hardness (( )), this will be intermediate hardness, this will be the mimimum hardness.

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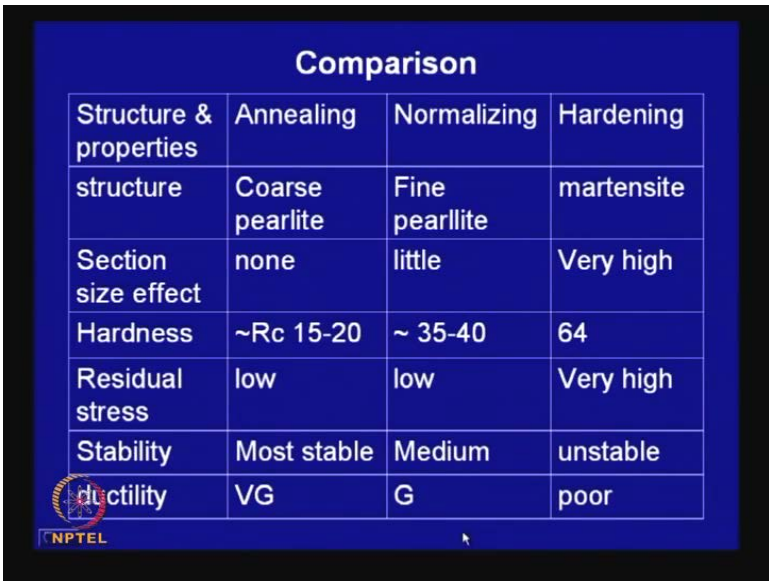

Comparison

Structure & properties	Annealing	Normalizing	Hardening
structure	Coarse pearlite	Fine pearllite	martensite
Section size effect	none	little	Very high
Hardness	~Rc 15-20	~ 35-40	64
Residual stress	low	low	Very high
Stability	Most stable	Medium	unstable
ductility	VG	G	poor

And this is the quick look at the summary, we can look at this anneahiling, normailising, hardening which are this characteristic structure which are listed here, may be next class we will look at little more detail also we will look at the courses of austenisation, which is quite important. So therefore, to sum up today we looked at martensite structure and its habit plane, why it develop forms on certain specific crystallographic plane, we also looked at continuous cooling process, and c c t diagram we also seen the relationship between t t t and c c t, and introduced the 3 different or common heat treatment processes, thank you.

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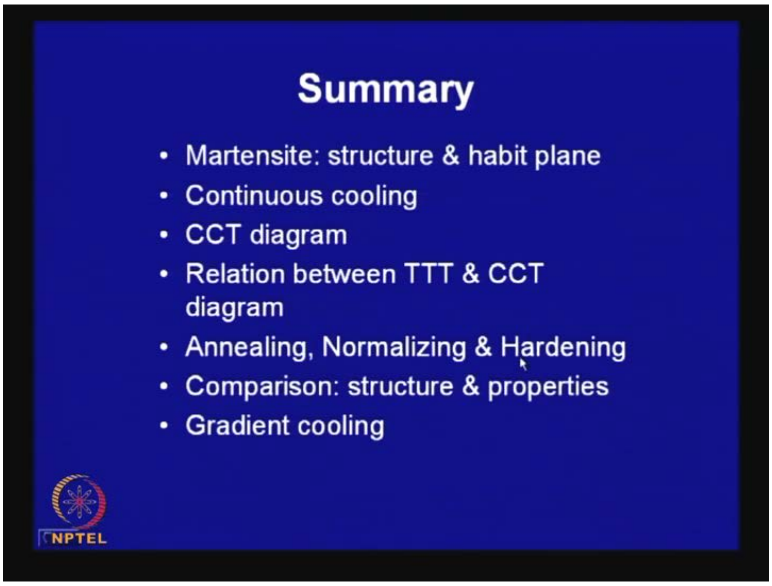

Summary

- Martensite: structure & habit plane
- Continuous cooling
- CCT diagram
- Relation between TTT & CCT diagram
- Annealing, Normalizing & Hardening
- Comparison: structure & properties
- Gradient cooling