Structure of Materials
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Lecture - 42
Chapter-08
Phase Transformations

The hardness of the martensite produced on quenching is the function of the amount of carbon, which is present in the martensite.

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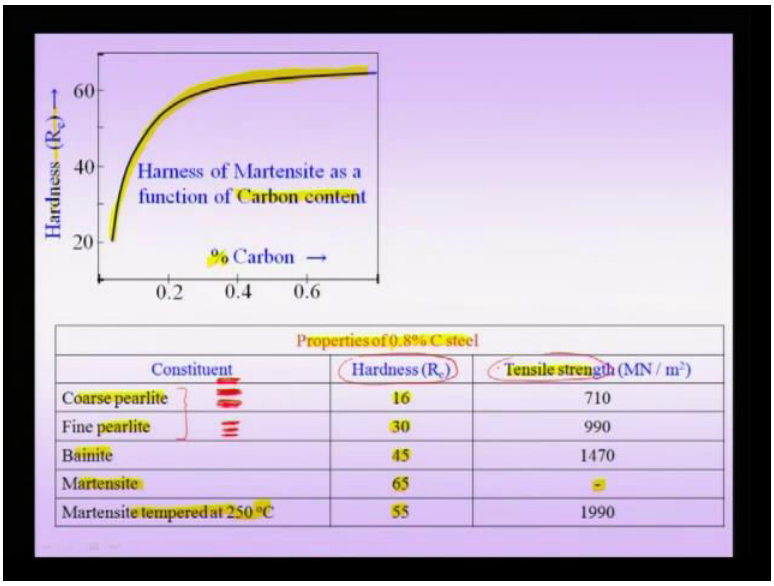

Properties of 0.8% C steel		
Constituent	Hardness (R$_c$)	Tensile strength (MN / m^2)
Coarse pearlite	16	710
Fine pearlite	30	990
Bainite	45	1470
Martensite	65	-
Martensite tempered at 250 °C	55	1990

You can see here that suppose I plot hardness in R c scale, you see that with increasing carbon percentage the hardness of the martensite increases. Parallelly, we had pointed out that though the hardness increases, but also showed as the ductility decrease and high carbon martensite may not be used for useful for practical applications. So, what we need to do is we need to temper this martensite, so that we have a good combination of ductility and strength.

So, here in this table below are listed properties of 0.8 percent carbon steel. Now, sometimes you may come across the question that what is the say for instance the tensile strength of hardness of 0.8 percent carbon steel. From this table below, you can see that this is not a well posed question, because of the reason that depending on the amount of first thing of course, the properties depend on the percentage of carbon definitely yes.

But, further it depends on the kind of microstructure you produce or in other words the kind of heat treatment you give to produce a specified microstructure. Now coarse pearlite has a hardness of about 16 R c, fine pearlite is even harder about 30 R c. Bainite is even harder about 45 R c, martensite is extremely hard, but as I pointed out it is spittle. And therefore, often it is difficult to do find the tensile strength as a specimen may break while doing the testing.

Therefore, when you temper martensite typically about 250 degrees Celsius the hardness falls a little bit, but in bargain you can actually get as combination of ductility and strength. Therefore, now you understand that not only the structure the composition determine the properties, but also the microstructure. And a direct handle on the microstructure is what we call by heat treatments. So, let me summarize this slide once more because this is a very important slide telling that the composition is important that the hardness of the martensite produced is increasing with the percentage of carbon.

But more, so if you compare even for a single composition like 0.8 percent plain carbon steel, the hardness can vary depending on the kind of microstructure you produce. The kind of micro constituent and even within a single micro constituent like pearlite. Suppose, I am comparing 2 kinds of pearlite fine and coarse pearlite, so this is say for instance schematically I show here coarse pearlite here and on the other hand suppose I have a fine pearlite here.

The hardness of these 2 and correspondingly the tensile strength etcetera are different because these hardness and tensile strength are microstructure dependent properties. So, this is the very important slide and all students of material science should keep this important point in view that depending on the microstructure, the hardness and all the other structures sensitive properties will change.

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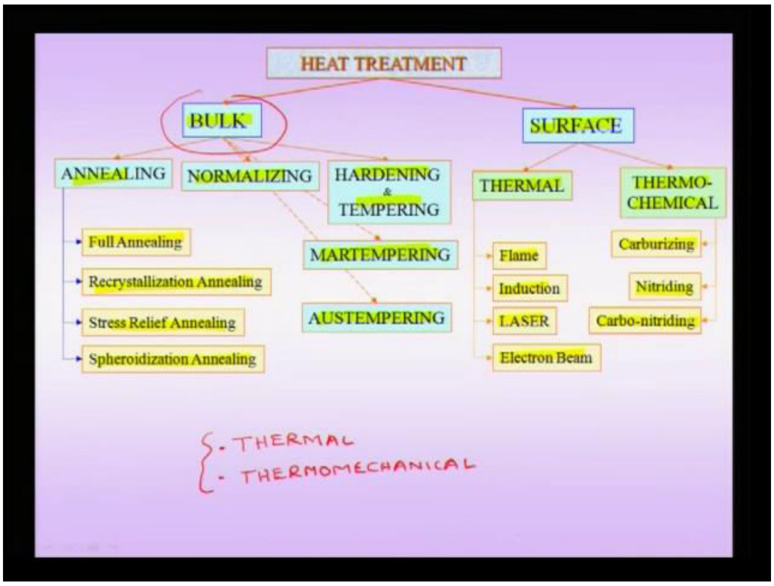

HEAT TREATMENT

BULK
- ANNEALING
  - Full Annealing
  - Recrystallization Annealing
  - Stress Relief Annealing
  - Spheroidization Annealing
- NORMALIZING
- HARDENING & TEMPERING
- MARTEMPERING
- AUSTEMPERING

SURFACE
- THERMAL
  - Flame
  - Induction
  - LASER
  - Electron Beam
- THERMO-CHEMICAL
  - Carburizing
  - Nitriding
  - Carbo-nitriding

- THERMAL
- THERMOMECHANICAL

In this slide here we have an over view of all kind of heat treatments and when you are trying to change the properties of material as I told you can get a handle on the microstructure by doing these heat treatments. But, the general super site is that we can have either thermal treatments which are called heat treatments or you can have thermo mechanical treatments. So, in thermo mechanical treatments not only do you apply heat, but you also may additionally work this specimen along with maybe work it at high temperatures.

So, that you can get a certain microstructure which is very desired for the properties. So, here is the broad listing of all the heat treatments that you can envisage there may be more, but this is a reasonably broad over view. Heat treatments that only affect the bulk are given on the left and heat treatments; that means, the heat treatments will affect the entire bulk are given on the left and those which are essentially targeted at the surface are given on the right cut.

The bulk treatments that you can envisage are annealing, normalizing, hardening and tempering, mar-tempering and aus-tempering. This is of course, with special reference to steels, but we will see that there are more kind of treatments which are we will encounter. In context to aluminum alloys and also other kind of treatments which we will not be covering in the current coarse. Then some of these names are familiar to us like normalizing, hardening. tempering, but there are 2 additional terms like mar-tempering and aus-tempering which we shall take up very soon.

In annealing we have full annealing, re-crystallization annealing, stress relief annealing and spheroidization annealing, we would briefly deal with some of these details of these processes and the student may actually refer to a good text on heat treatment to understand the details. Here the focus being on the fact that you can actually engineer the microstructure by doing heat treatment. That means, not only are you having a good understanding of the crystal structure and therefore, the resulting properties, but also a handle on the microstructure.

For surface treatments they can be thermo thermal surface treatments like flame hardening, induction hardening, laser hardening, electron beam hardening or there can be thermo chemical treatments in which case not only are we effecting the heating the surface, but also we are altering its composition. The important once in the context of steel are carburizing, nitriding and carbo-nitriding.

So, to summarize this slide we can have thermal treatments and thermo mechanical treatments further of course, we can even envisage treatments involving magnetic fields and other kind of external stimuli, but we restrict ourselves here to basic need to thermal treatments. In thermal treatments we have those treatments which affect the entire bulk or those treatments which affect the surface, focus being on the once related to steel.

Some of these treatment like annealing, normalizing, hardening, we have encountered before you will see a little more about tempering in the coming slides. And we additionally introduce 2 new terms mar-tempering and aus-tempering. Annealing itself comes in many types and some of these types are listed here full annealing, re-crystallization annealing, stress relief annealing and spheroidization annealing. Each 1 of these annealings is especially intended to produce a specific change in the properties and the microstructure and for instance.

In re-crystallization annealing you try to replace cool work grains with re-crystallized grains; that means, that we will have to understand what is re-crystallization which we will do, so in 1 of the coming slides. As far as surface treatments are goes they are those which effect the chemistry of the surface like which I call thermo mechanical treatments.

And these include carburizing, nitriding and carbo-nitriding, in carburizing you introduce carbon on to the surface at high temperature, nitriding you introduce nitrogen and in carbo-nitriding it is a combined process. In thermal treatments you can harden the material by heating the surface either using flame induction sources; that means, R f sources laser or electron beam. So, this is a broad overview of the treatments which we can undertake to change the properties of steel.

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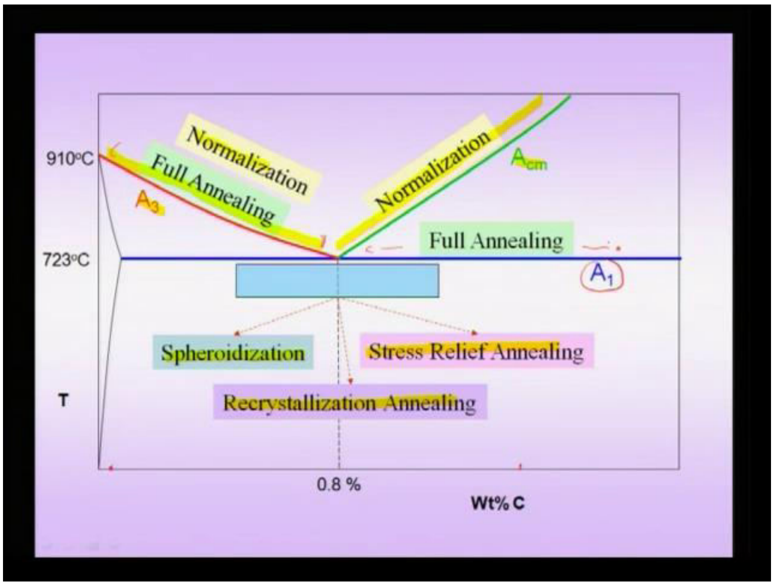

Now where are the temperature ranges in which you actually carry out these treatments and what is the reason we will see here. Now typically the range of useful products is as we have seen that is around centered around this right from low carbon steel which might start here to certain high carbon steel. So, we see that there are those treatments which are carried out below the A 1temperature and these treatments are the spheroidization treatment, the stress relief annealing treatment and the re-crystallization annealing treatment.

There are those which are carried out above the A 3 or the A c m line like the normalization. So, we carry out normalization in the temperature region which is above the A c m line for hyper eutectoid steels and above the A 3 line for the hypo-eutectoid steels. Full annealing on the other hand is carried about above the A 3 line for the hypo-eutectoid steels like here.

So, when you want to do full annealing you will carry out it in the region of above A 3 for hypo eutectoid steel; however, for hyper-eutectoid steels the full annealing is carried out only above the A 1 line and not above the A c m line. So, this is the range we carry out we will see the reason very soon. So, therefore, there are preferred temperature regions in which these treatments are carried out and it should be remembered that whenever you are talking about a heat treatment.

It cause industry in terms of time it also cause in terms of capital investment, because we need furnaces in which these material have to be put and heat treated. And further some of these furnaces may be batch type which means that it can actually slow down your production. So, therefore, optimizing the heat treatment for a desired microstructure and properties is very, very important.

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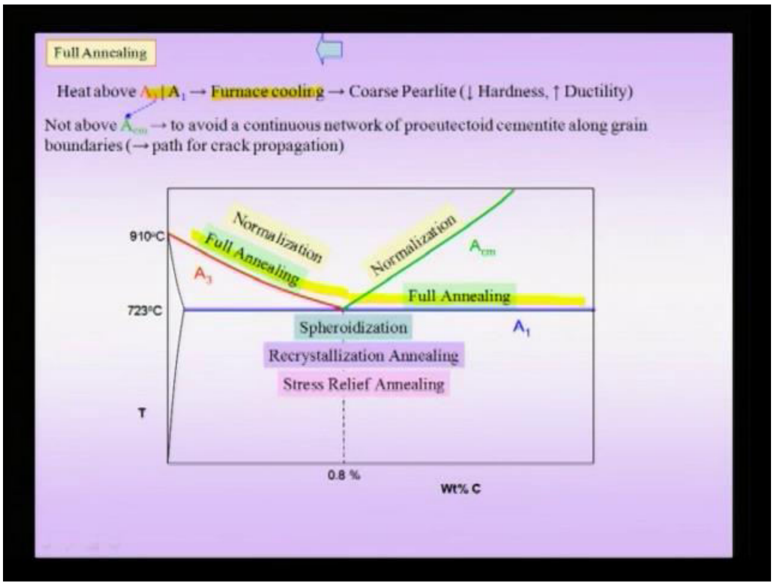

Full Annealing

Heat above A_3 | A_1 → Furnace cooling → Coarse Pearlite (↓ Hardness, ↑ Ductility)

Not above A_{cm} → to avoid a continuous network of proeutectoid cementite along grain boundaries (→ path for crack propagation)

Now what is full annealing? In full annealing we heat above the A 3, A 1 line like we have seen here, we heat in this region. So, this is my A 3 line above for the hypo-eutectoid steels and A 1 line above the hyper-eutectoid steels. We basically carry out a furnace cooling; that means, it will cool very, very slow and we have seen that we get a cooling rate of the out of 10 power minus 3 or so Kelvin per second Kelvin.

So, this is we have listed all the rates of cooling here, for various furnace and we saw that we get about 10 power minus 5 to 10 power minus 3 Kelvin per second which is a very, very low slow cooling rate.

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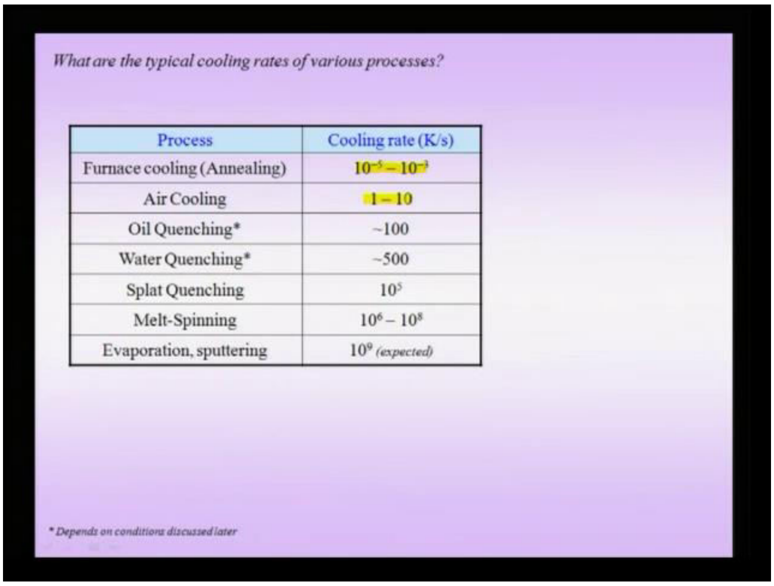

What are the typical cooling rates of various processes?

Process	Cooling rate (K/s)
Furnace cooling (Annealing)	$10^{-5} - 10^{-3}$
Air Cooling	$1 - 10$
Oil Quenching*	~100
Water Quenching*	~500
Splat Quenching	10^5
Melt-Spinning	$10^6 - 10^8$
Evaporation, sputtering	10^9 *(expected)*

* *Depends on conditions discussed later*

Compared especially to treatments like air cooling which itself is a few orders of magnitude faster.

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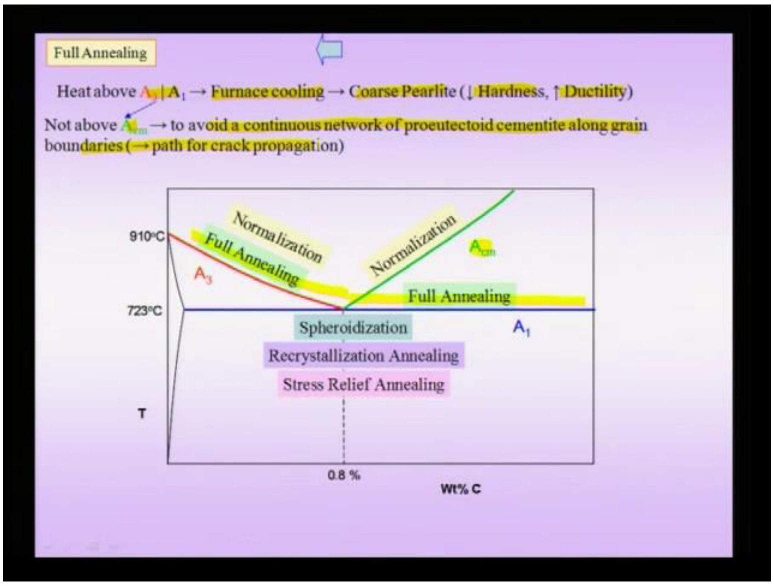

Full Annealing

Heat above A_3 | A_1 → Furnace cooling → Coarse Pearlite (↓ Hardness, ↑ Ductility)

Not above A_{cm} → to avoid a continuous network of proeutectoid cementite along grain boundaries (→ path for crack propagation)

And the final product as we have seen is coarse pearlite which has not so high hardness, harder than of course a pure iron. But, not so higher hardness as compared to what we can get by say quenching the steel, but we have increased ductility. We do not carry out this treatment above the A c m, for instance full annealing is not carried about above A c m. This is to avoid a continuous network of pro-eutectoid cementite along the grain boundaries. And we have noted previously and I have to go to the board to explain you why this so? That this continuous network is bad news as far as the properties go.

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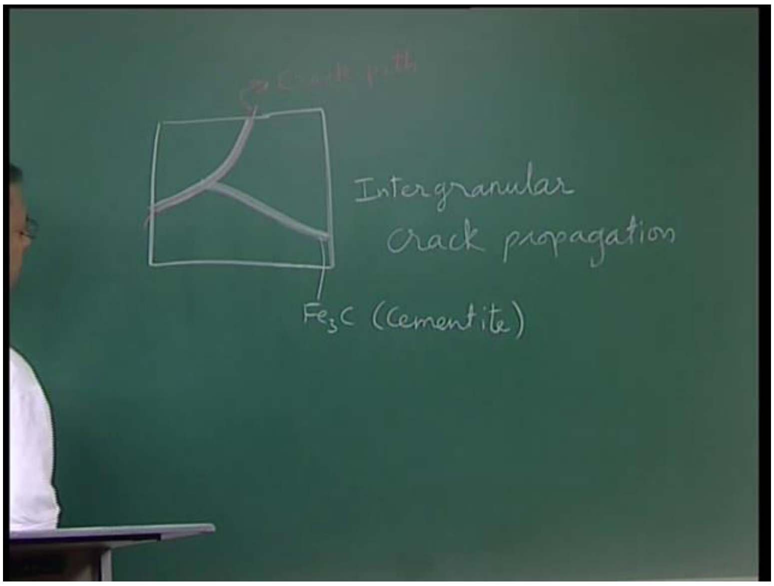

So, for instance suppose I now slowly cool and you have a poly crystalline austenite at high temperatures and I do my heat treatment not above A 1, but above A c m. What might happen is that, so you have a polycrystalline grain boundary. So, what might happen is that when you slowly cool from above you will produce a continuous network of cementite along the grain boundaries. Now the cementite is a brittle phase a hard phase therefore, continuous cracks can propagate along these paths and therefore, the material may fail in inter-granular fashion.

So, this is my continuous network of cementite along the prior austenite grain boundaries, you have cracks which can propagate along the grain boundaries of the prior austenite. And therefore, the material will have very poor toughness especially under impact and therefore, you do not want such a microstructure. And to avoid such a microstructure what we do is that we carry out full annealing not above the A c m line, but we carry it above the A 1line which is here.

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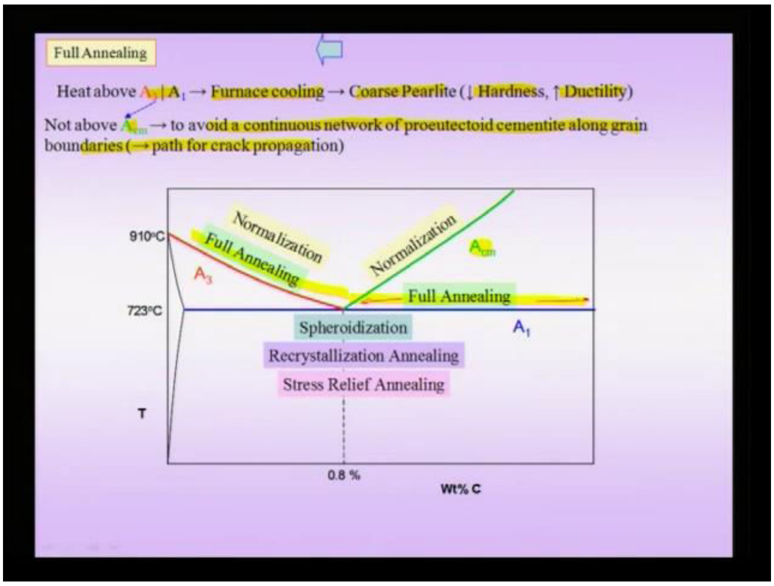

Full Annealing

Heat above A_3 | A_1 → Furnace cooling → Coarse Pearlite (↓ Hardness, ↑ Ductility)

Not above A_{cm} → to avoid a continuous network of proeutectoid cementite along grain boundaries (→ path for crack propagation)

So, this is my range in which I carry out my full annealing this is my. So, this full annealing of course produces the microstructure which has very low residual stresses and is good in terms of ductility.

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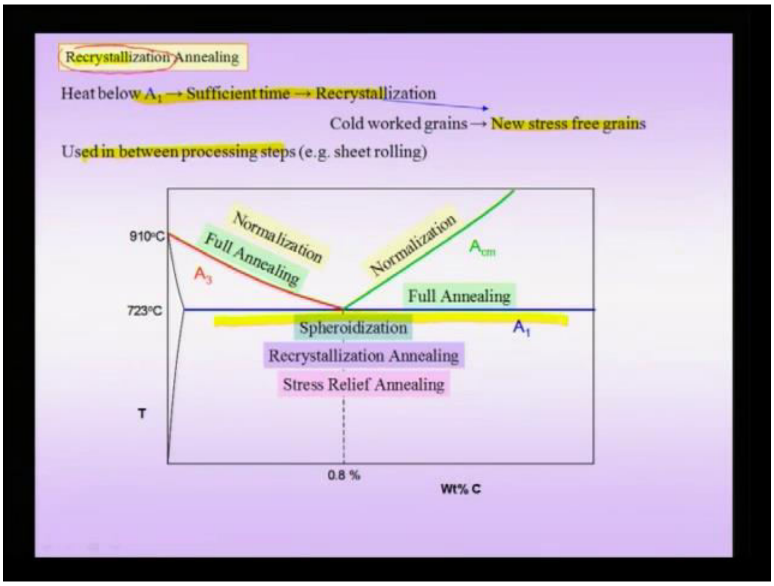

Recrystallization Annealing

Heat below A_1 → Sufficient time → Recrystallization

Cold worked grains → New stress free grains

Used in between processing steps (e.g. sheet rolling)

Re-crystallization annealing and we will try to understand this term re-crystallization in detail later on. And we will see it is not just a phase transformation, it is a term related to microstructure transformation. And typically you would like to carry out re-crystallization to restore ductility in a material. Suppose, I am cold working sheets what might happen is that after I cold work say give us certain reduction say 20 percent reduction on the sheet the material becomes harder because a strain hardening. And therefore, the ductility of the material comes down and to restore this ductility.

So, that you can further deform the sheets you would carry out such kind of re-crystallization annealing in between process steps. For other reasons also you may want to carry out re-crystallization annealing to produce a microstructure in which we have strain free grains. Typically, this is done below A 1 and you get sufficient time, so that these cold worked grains are replaced by new stress free grains.

So, essentially you have material at the end which is ductile where the defect density is small the dislocation, density is small. And the material further can be worked if necessary, so in re-crystallization annealing which is carried out just below A 1 temperature. You have a material finely produced which is also very, very ductile. And this is carried out below A 1 for hyper and hypo-eutectoid steels.

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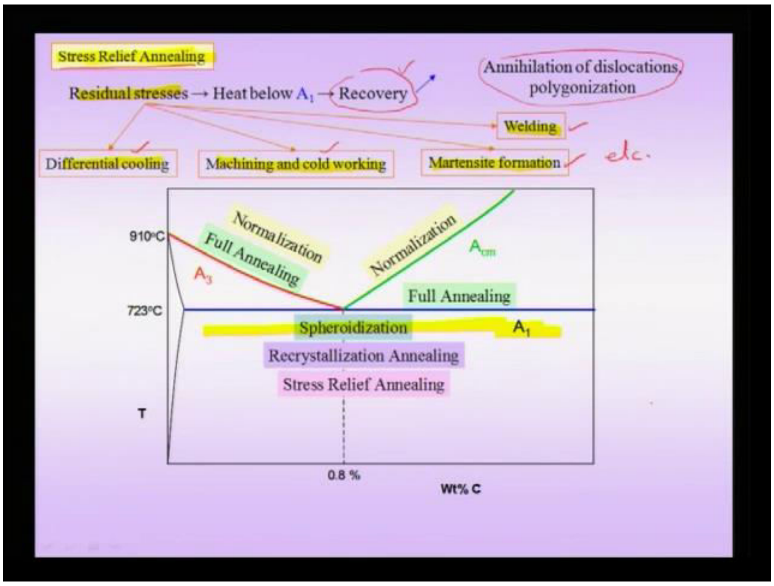

Stress Relief Annealing

Residual stresses → Heat below A_1 → Recovery

Annihilation of dislocations, polygonization

Welding

Differential cooling

Machining and cold working

Martensite formation

etc.

Stress relief annealing is given to get rid of residual stress, now where is the temperature region in which carries stress relief annealing is again its below the A 1 temperature. And you would like to out below the A 1 temperature and the reason that you have residual stresses here. The once we are talking about are not the once which are associated with typically with micro structural defects, but we are talking about that which is resulting from differential cooling, machining and cold working.

And even martensitic transformation we had noted is associated with lot of strains, volume changes we have already noted the technical term for that is the main distortion. And therefore, martensite formation also gives rise to considerable amount of residual stresses in the material. These residual stresses could also come from sources like welding wherein a pool of material forms and solidifies and in this process you may have residual stresses forming in the material.

These residual stresses they may be coming from as we have pointed out from various sources like differential cooling of a in A 2phase material or surface cooling at a different rate from the interior machining and cold working matensitic transformation welding and etcetera. So, these are just a few sources there could be other sources could be bad for the component. So, what might happen to the component is that the component by warp in service or warp after during the further steps in for instance component formation.

Suppose, you had a welded component and you want to machine it further in during this step the component may undergo warp-age page. And therefore, these residual stresses could be deleterious to the material in an earlier class we had noted that how residual stresses can even be beneficial. So, we should not construe that always residual stresses are detrimental to the material. There could be beneficial effects of residual stress in many circumstances, but here we are talking about the deleterious effects of residual stress.

And how to get rid out of this residual stress via a process known as stress relief annealing, so this is my stress relief annealing process. So, to get rid of this residual stresses I heat below A 1 as I pointed out and this leads to a phenomena known as recovery which we will deal in a little it is a technical term and we will talk about what is recovery in little more detail in the coming slides.

And during recovery there is of course, there is lot of annealational dislocations and other micro structural defects, but the focus is on the macroscopic residual stresses which also are reduced. And the material therefore, has less chance of warping during further processing steps or during service.

So, in this current slide the important kind of annealing known as stress relief annealing is mentioned and you would like to carry this out to get rid of the various source of residual stresses. And here we are not replacing the entire strains, stress free grains, strained grains with stress free grains, but we are trying to locally rearrange this stresses. So, that the final product is low in stresses which can reduce the warping

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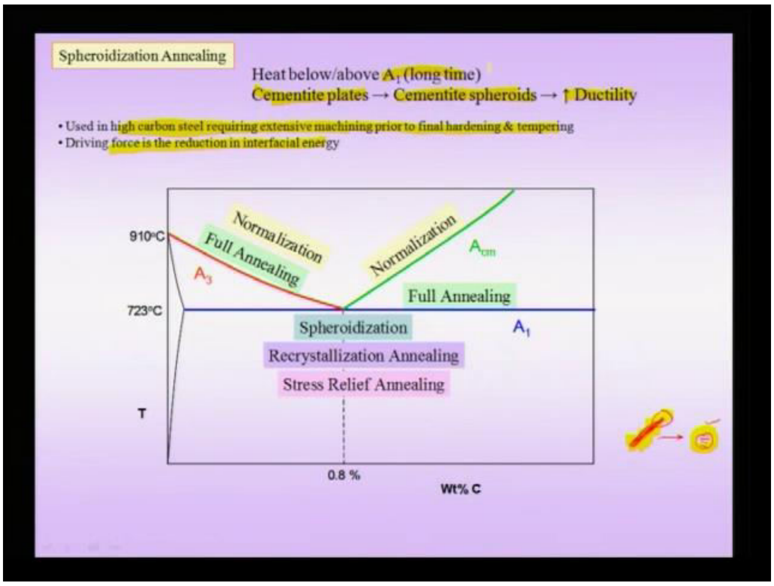

Spheroidization Annealing

Heat below/above A_1 (long time)

Cementite plates → Cementite spheroids → ↑ Ductility

- Used in high carbon steel requiring extensive machining prior to final hardening & tempering
- Driving force is the reduction in interfacial energy

Now spheroidization annealing is specially carried out not in all kinds of materials, but it is carried out in high carbon steels requiring extensive machining prior to finely hardening and tempering. And in this there are cementite plates and these cementite plates as we have pointed out cementite is a brittle phase, we replace with cementite in the form of spheroids.

So, initially we may have an cementitie which is has this morphology of plates and we try to replace this with a morphology which is more like a swear. And in this process we are increasing the ductility, because these plates corners can act like stress concentrators. And in the form of sphere such kind of stress concentration does not take place. And therefore, if you are doing this spheroidization annealing these cementite plates can be replaced by cementite spheroids which increase the ductility of the material.

So, as I pointed out this is typically done in high carbon steels requiring extensive machinery a machining prior to final hardening and tempering. The reduction in surface energy or the interface energy is a responsible for this because if you look at the plate the interface energy per unit volume for a plate, interface area per unit volume which also translates into interface energy per unit volume is larger as compared to that for a sphere which has a least interface energy per unit volume of the material.

Therefore using this reduction in interfacial energy as the driving force, we can carry out spheroidization annealing to increase the ductility. This typically done as we have saw before above A 1 below or above A 1, but for an long period of time. So, this is requires a long time because this process is very slow and unless extremely required this kind of a process should not be carried out.

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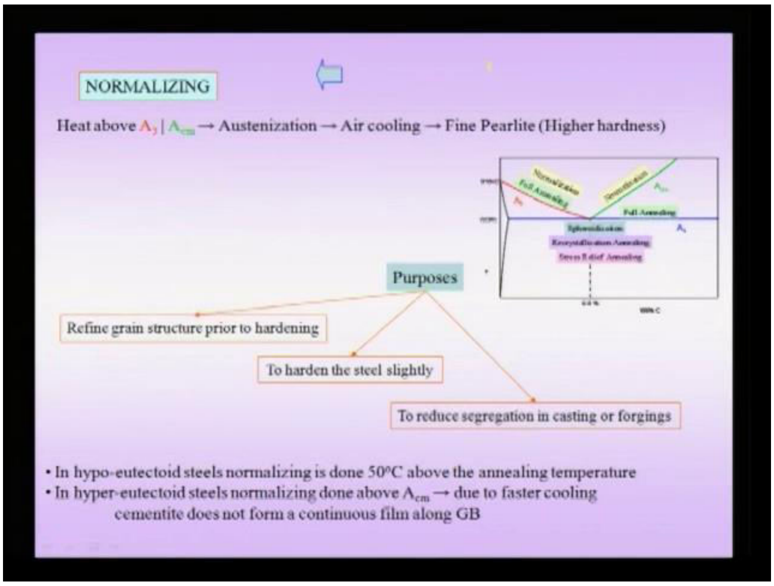

NORMALIZING

Heat above A_3 | A_{cm} → Austenization → Air cooling → Fine Pearlite (Higher hardness)

Purposes

- Refine grain structure prior to hardening
- To harden the steel slightly
- To reduce segregation in casting or forgings

- In hypo-eutectoid steels normalizing is done 50°C above the annealing temperature
- In hyper-eutectoid steels normalizing done above A_{cm} → due to faster cooling cementite does not form a continuous film along GB

Now, the next term we have already noted is what we call normalizing and we had referred to normalizing again like full annealing in the T T T or C C T diagram.

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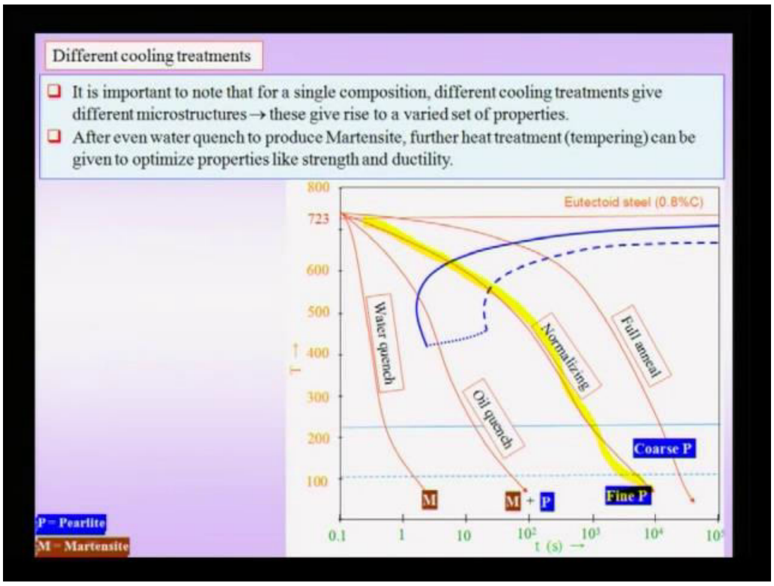

Different cooling treatments

- It is important to note that for a single composition, different cooling treatments give different microstructures → these give rise to a varied set of properties.
- After even water quench to produce Martensite, further heat treatment (tempering) can be given to optimize properties like strength and ductility.

So, we had noted that normalizing is such a kind of treatment in which you produce you cool at a rate such that it intersects the pearlitic curve and the product is typically pearlite fine pearlite. As compared to some of the other process which involved either higher or lower cooling rate.

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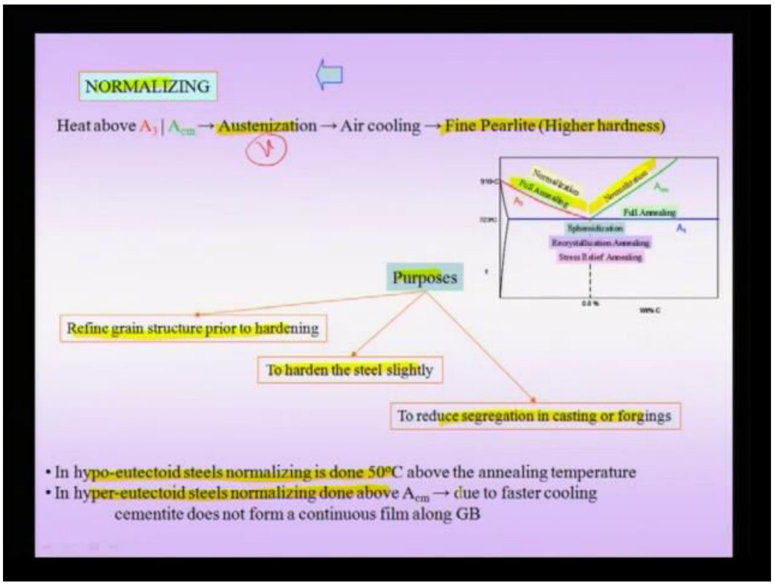

NORMALIZING

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- In hypo-eutectoid steels normalizing is done 50°C above the annealing temperature
- In hyper-eutectoid steels normalizing done above A_{cm} → due to faster cooling cementite does not form a continuous film along GB

So, in normalizing you heat above A 3 or A c m for hyper-eutectoid seal A 3 for hyper-eutectoid steel. And you cause austenization; that means, you the starting product is gamma. Then as we have seen that you do air cooling, an air cooling produces fine pearlite with high hardness. The purposes of normalizing is to refine the grain prior to hardening to harden steel slightly or to reduce segregation in castings and forging. So, there are multiple purposes for which normalizing is used, but the final microstructure is fine pearlite.

And in hypo-eutectoid steel the normalizing is done 50 degrees above the annealing temperature while in hyper-eutectoid steel it is done above the A c m. In this case again we might wonder that why is that previously I pointed out that there could form a continuous network of you seen that it forms a continuous network along grain boundary in the cementite.

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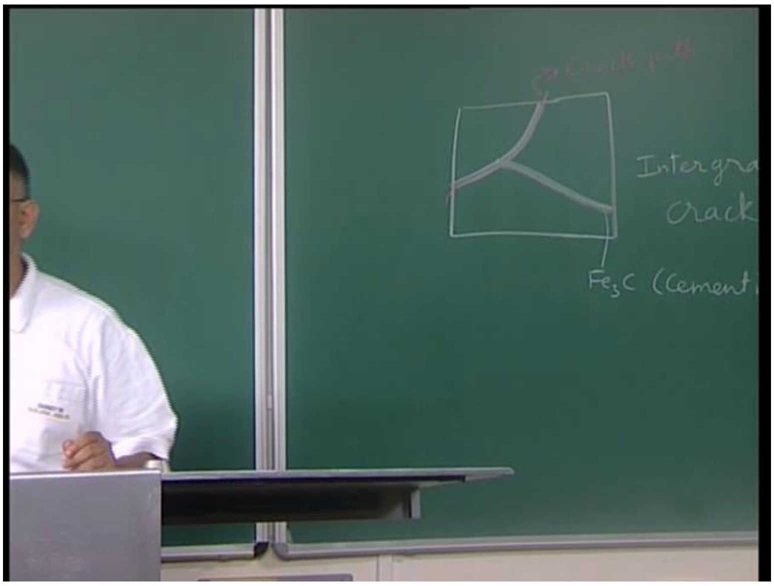

So, in this also we are taking the steel above the A c m temperature and cooling. So, why not that discontinuous network is is a problem.

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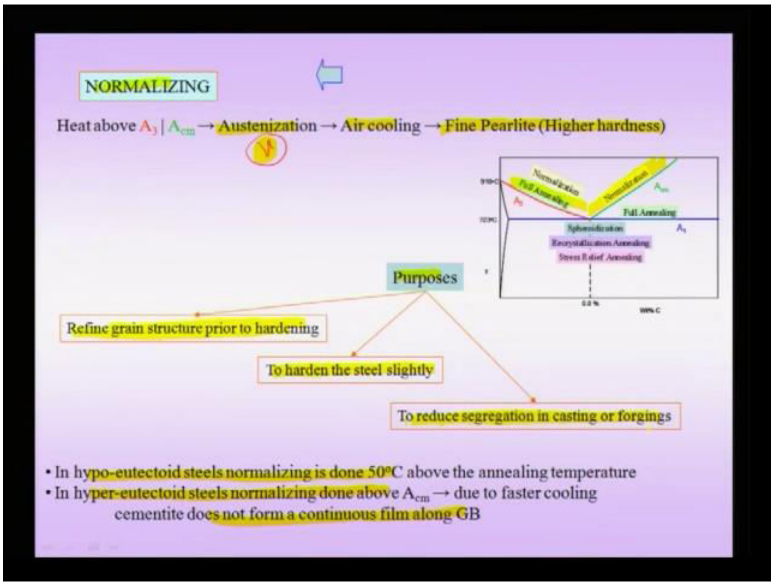

NORMALIZING

Heat above A_3 | A_{cm} → Austenization → Air cooling → Fine Pearlite (Higher hardness)

Purposes

Refine grain structure prior to hardening

To harden the steel slightly

To reduce segregation in casting or forgings

- In hypo-eutectoid steels normalizing is done 50ºC above the annealing temperature
- In hyper-eutectoid steels normalizing done above A_{cm} → due to faster cooling cementite does not form a continuous film along GB

The reason is that we are cooling very faster in normalizing and like in annealing processes. And this fast cooling avoids this continuous network of film along the grain boundaries. So, therefore, in normalization process in which involves the faster cooling we can actually heat above A c m before we start our cooling. And so to summarize what is this normalizing process we start with a heat the substance to a gamma phase speed, air cooling to produce a fine pearlitic microstructure which is a higher hardness.

Higher hardness as compared to say for instance coarse pearlite, but definitely lower than martensite as we have seen before. This process can be used to refine the grain structure prior to hardening to harden steel slightly or to reduce segregation in castings and forgings. This could be a problem for instance suppose you are casting a very large amount of material there could be some segregation and this can be reduced.

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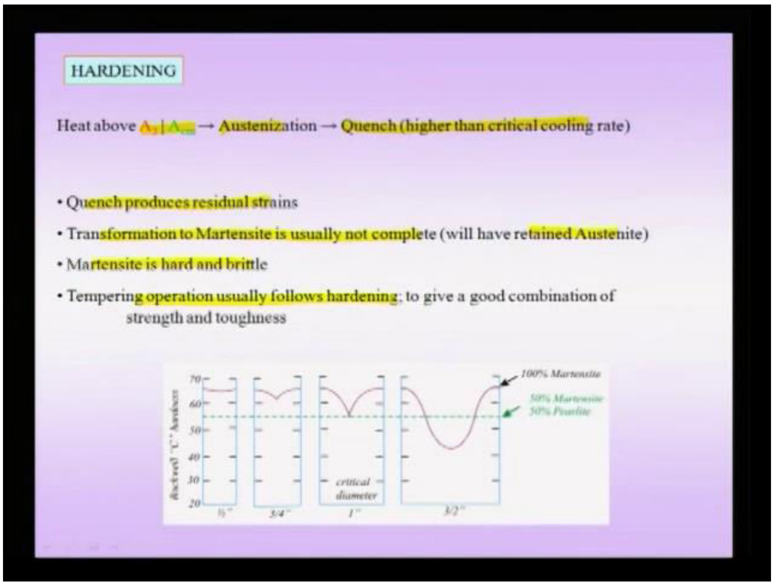

HARDENING

Heat above A_3 | A_{cm} → Austenization → Quench (higher than critical cooling rate)

- Quench produces residual strains
- Transformation to Martensite is usually not complete (will have retained Austenite)
- Martensite is hard and brittle
- Tempering operation usually follows hardening; to give a good combination of strength and toughness

Now, we take up this process hardening and we have already noted that to produce hardening we need to produce the micro constituent micro constituent or the phase called martensite. And we already seen that this formation of martensite involves this being distortion and we have understood it via the invariant plain strain construct. Now, we already know that we have to heat it above the A 3 or A c m temperature. So, above the A 3 or A c m temperature, so that we can get a full gamma.

And after this gamma is produced we quench to avoid the nose of the C C T diagram which is; that means, we have to cool it at a critical rate. And so, that we can produce martensite in the microstructure, this quench process produces residual stress, strains and in the material.

And further we have to note that this transformation to martensite is usually not complete; that means, we will have a certain amount of residual or retained austenite.We also noted that martensite is a harden brittle and therefore, we have to give a tempering operation immediately after a hardening. So, that we have a good combination of ductility and strength.

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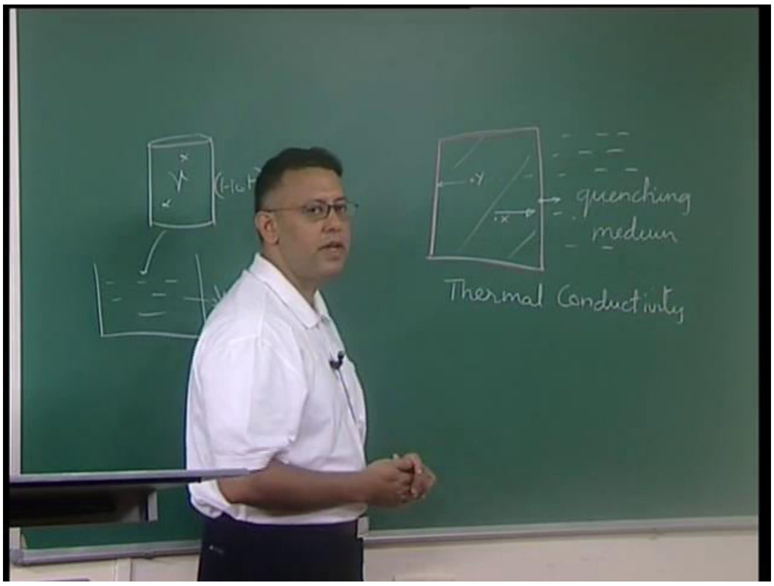

Now an important point in this context is that suppose I have a cylinder and I quench it in a medium. Suppose, this is my bath having water and I put it inside this water bath, so this is water bath at room temperature. So, this is a gamma and this is the hot, then it is obvious that suppose this is my body. And this is my quenching medium, then only the surface of the quenching medium which is this part. You can see if it is a complete bath and all the surfaces will feel the effect of the quenching media.

That means, immediately the heat from here will be withdrawn from the surface area and this will immediately be cooled down to the temperature close to that of the quenching media. However, even if you quench this surface very fast the interior of the material say a point x in a material or a point y in the material. These points are not in direct contact with the with the quenching medium and therefore, the way that this point x is going to be cooled is via conduction.

That mean heat has flow to the surface and has to be removed, now this; obviously, depends on the thermal conductivity of the material. So, this depends on the thermal conductivity and not merely a function of the what we might call the effect of the quenching media. So, the point y for instance might actually you may draw heat towards this surface.

And some of the heat may also flow to this surface, but essentially the interior points within the cylinder say which could be located some were here or here within the cylinder. Those interior points within the cylinder do not feel the direct effect of the quenching media and they are dependent on the thermal conductivity of the material being quenched. And therefore, there they do not phase such an severe cooling rate as the surface phases.

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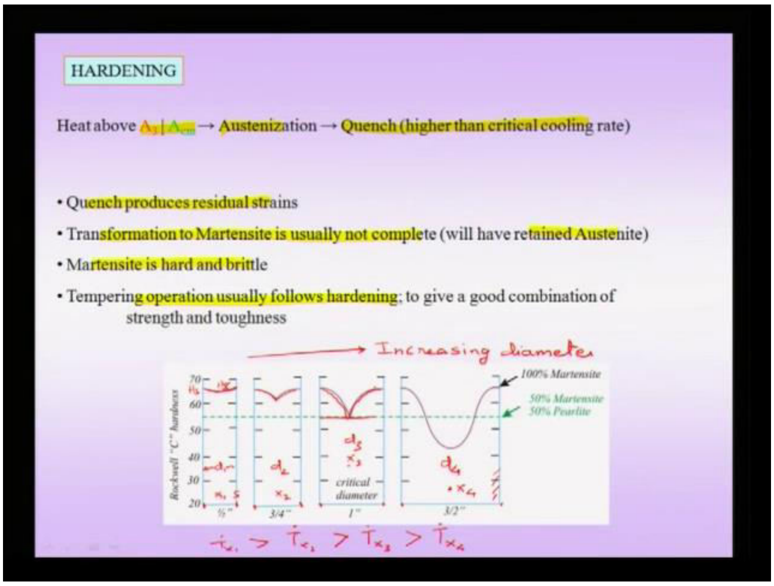

HARDENING

Heat above A_3 | A_{cm} → Austenization → Quench (higher than critical cooling rate)

- Quench produces residual strains
- Transformation to Martensite is usually not complete (will have retained Austenite)
- Martensite is hard and brittle
- Tempering operation usually follows hardening; to give a good combination of strength and toughness

Increasing diameter

$\dot{T}_{x_1} > \dot{T}_{x_2} > \dot{T}_{x_3} > \dot{T}_{x_4}$

So, what is the consequence of this? What is the consequence of the fact that now only my surface is filling my quenching rate. So, what might happen is that if you take a thin enough cylinder, so this is the first example I am taking a thin enough cylinder. For instance this is about half an inch in diameter and the point x in the middle for instance is not too far away from the surface say which is s. And therefore, heat can could quickly be conducted away and over all the material fields are reasonably high cooling rate.

And therefore, if you plot the hardness you will see that the hardness dips a little bit, but the hardness on the surface is not much lower than the much higher than the hardness of the interior which is at a point x for instance. Now if I make this cylinder a diameter larger then the point x for instance the middle, feels a lower cooling rate as compared to that x 1 which is here. So, the x 2 fields are lower cooling rate and if I keep on increasing my diameter a point in the center which is x 3 fields are even lower cooling rate.

And if I increase a diameter to say 1 and half inches, so here the x 4 will feel an even cool slower cooling rate. So, I can write this down as T x 1 dot is higher than T x 2 dot is higher than T x 3 dot is higher than T x 4 dot. Even in the case for instance suppose I take a thick cylinder the regions close to the surface are feeling a high cooling rate, but not the points close to the interior. Now what happens; that means, that suppose I take A three fourth in cylinder or a certain larger cylinder.

So, if this diameter is say d 1 which is in this case example is half an inch, but could be any number. And this is d 2 and this is d 3 and I have a d 4. So, what happens that with increasing diameter, so I have my increasing diameter the interior of the material the central point which is marked as x feels a lower and lower severity of the quench. Therefore, the hardness of such a material keeps on decreasing toward the center and there comes a point where, I produce only 50 percent martensite at the center.

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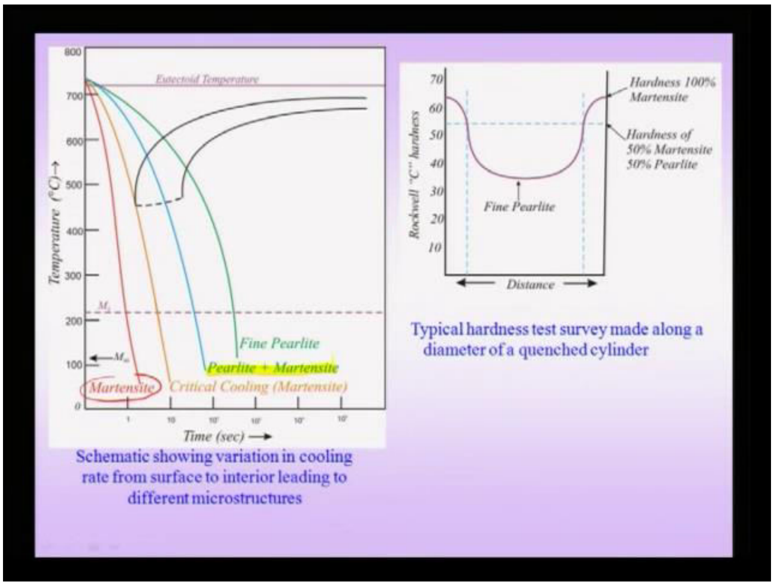

Schematic showing variation in cooling rate from surface to interior leading to different microstructures

Typical hardness test survey made along a diameter of a quenched cylinder

So, the remaining 50 percent, so what happens is that, so I can see this is schematically in this diagram. So, if you have a thin enough cylinder I produce full martensite, but if I increase the thickness of cylinder I produce a combination of pearlite and martensite.

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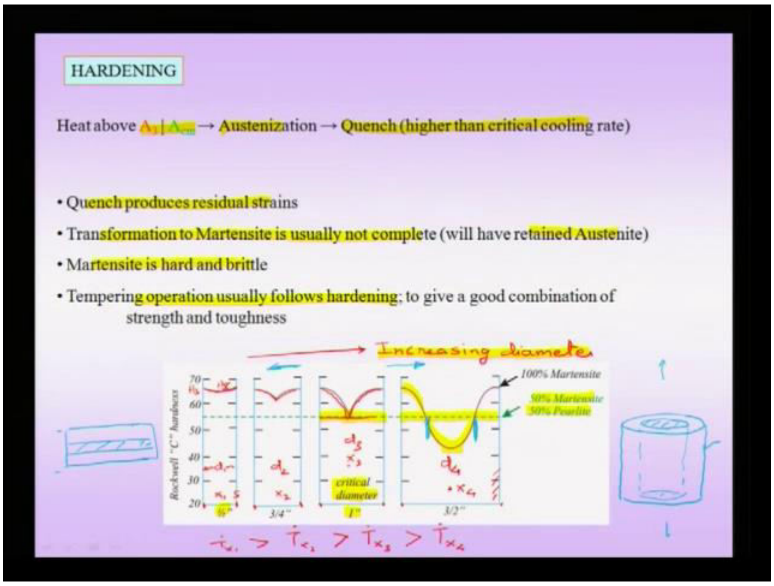

HARDENING

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Now this combination of pearlite and martensite because the untransformed. So, this combination of pearlite and martensite is not as hard as my full martensitic structure. So, this arbitrary cut off where I produce 50 percent martensite and 50 percent pearlite is called the critical cooling rate to which I need to cool my which is for instance. Here the critical cooling rate such that throughout the section I at least obtain 50 percent martensite.

So, suppose I have a diameter which is say for instance in this example the critical diameter is 1 inch. If I take a diameter which is to the left of this, so I choose a diameter which is smaller than the critical diameter. Then I would obtain more than 50 percent martensite and if I choose the diameter of which is to larger than the critical diameter then there will be lesser amount of martensite.

In fact, there will be more of pearlite and if there is less amount of martensite, then you would notice that the hardness of the center is even below that which you have obtained for the critical cooling rate and therefore, the hardness falls towards the center. Now, such a material as you can see has not been through harden, truly a material which has been through harden this for instance. This is example in half an inch material, the as you go from go on increasing the diameter the hardness falls at the center, but you do tolerate about 50 percent martensite which you call a critical diameter at which if you cool.

Then you at least have 50 percent martensite to give you some amount of or the requisite amount of hardness , but diameter is larger than 50. This critical diameter would have at the center hardness even lower than that for the critical diameter. And wherein you obtain more pearlite then and; that means, its less than 50 percent martensite here in this region of the sizes. So, you have here in this range of the diameters; that means, you have now a sample

In which you have a central code say for instance suppose, I am talking about a cylinder which is long in this section. That means, I have a central core which I am shading here and this central core does not have even 50 percent martensite. And therefore, is soft as compared to the surface which of course, is felt full severity of a quenching medium and therefore, is hundred percent martensite. So, therefore, I need I can only harden that much through sections by quenching which is for instance below the critical diameter.

That means, you are now placing a limitation on the amount or the thickness of the sections which can be hardened. Of course, the geometry of the specimen need not be cylindrical it could be plate like, but again if you using a plate like specimen which of course, using a cross section here. Then you would note that if I choose a plate which is more than the critical thickness. Then what will happen is that the there will be a central core region which has less than 50 percent martensite and therefore, has not been through hardened.

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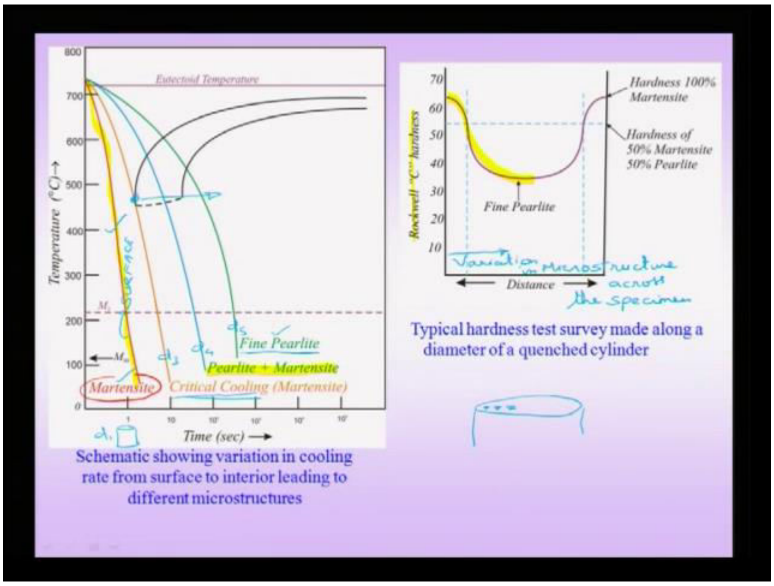

Schematic showing variation in cooling rate from surface to interior leading to different microstructures

Typical hardness test survey made along a diameter of a quenched cylinder

Now, this can be understood using C C T diagrams, as in a single diagram now we are drawing multiple cooling curves. Now these multiple cooling curves are not for different methods of cooling. For instance earlier we had seen multiple cooling curves wherein we said that I am doing full annealing inside of one as once I may be doing normalizing. That means, cooling in air 3rd case I could actually be cooling in by quenching in oil etcetera, but in this case we had actually quenching this material in same a cooling medium like water.

Of course, I keep the conditions constant like for instance I just quenched into water I do not vigorously shake it or anything. Then I note that the surface could be cooling at a rate as shown by the red curve. So, this could be my curve which is representative of the surface which is falling forming full martensite, so this curve could be the one which is for the surface. And this point could be for just below the surface and this point could be at the center of the cylinder for instance.

Now, alternate way of thinking of the same curves is that I can think of this as a material which is having a certain diameter. Say, d 1 and for instance this critical cooling we have noted is a diameter which is d 3. So, for critical cooling rate this will be a diameter d 3 and this could be thicker diameters like d 4 and d 5. So, now we have extended the utility of the C C T diagrams by drawing cooling curves. Now, for different cooling treatments, but for either different diameter cylinders or specimens with different thicknesses or tracking the cooling at different points within a thick specimen for instance.

The surface could be feeling a very high cooling rate while some point in the interior could be feeling for instance. Just the critical cooling rate in which you will form 50 percent martensite or somewhere deeper in the material you will just get fine pearlite. That means, there is a microstructure variation within the sample while we are quenching the sample and; that means, that we have to be little careful. That whenever we dealt the C C T diagrams we had talked about quenching and producing martensite.

What essentially we were talking? Was that the sample surface is forming martensite not the entire sample. Of course, we are talking about a slow cooling treatment the entire sample is equilibrium and therefore, you are getting say for instance coarse pearlite. Then the entire sample will be coarse pearlite, but in the context of quenching we have to be little careful. That even though my sample surface is getting quenched at a very high rate and therefore, I am producing full martensite the sample interior could be left with the only pearlite or fine pearlite.

That means that there is a variation in microstructure from interior outside to interior. So, now, I cannot draw any uniform microstructure, so there is a and needless to say such a variation in microstructure change produces resultant changes in the hardness for instance and other properties. Of course, measuring other properties on in individual sections may be difficult, but hardness is easy to measure. We can put you put a indenter on the surface close to the surface for instance suppose, I took a made a cylinder and I quenched it.

So, what I can do is that for such a cylinder I can put a indenter at this point close to the surface take it slowly put various indentations at various points. And therefore, measure the variation in hardness and such a plot has been as you have seen before shows that the hardness from the surface falls towards the interior. So, therefore, now I need to worry about the fact that if my sections are very thick there is going to be a variation in microstructure.

And therefore, there is going to be a variation in properties; that means, there is no uniform properties that the material have and whatever tensile properties you measure would be an average. Sometimes this may be beneficial because, sometimes you would want a hard surface and a cut off interior. So, such a treatment would automatically give you such a hard surface and a cut off interior, but then the understanding the behavior of or deformation behavior, such a kind of a microstructure could be rather difficult.

Now this is one of the motivations as we shall see later to produce what we call alloy steels. So, that my C C T diagrams are moved towards the right; that means, in a alloy steels you will note that the nose of the T T T diagram which is typically as we have noted. This nose is of the order of just a second; that means, the quenching rates you need to employ are very, very large, but suppose you are able to move the nose of the T T T diagram to the right.

That means that I can apply less severe quenching rates to produce martensite, then such a material not only will be easily hardenable. Hardenable being the ability to harden with the least severe quench, so I will repeat again that hardenability is a technical term. It is the ability to harden a material by producing martensite via the least possible severe quench and that is one benefit of moving the T T T diagrams to the right. And that can be done via alloying as I pointed out, but additionally also the thermal stresses produced in the material are also going to be low.

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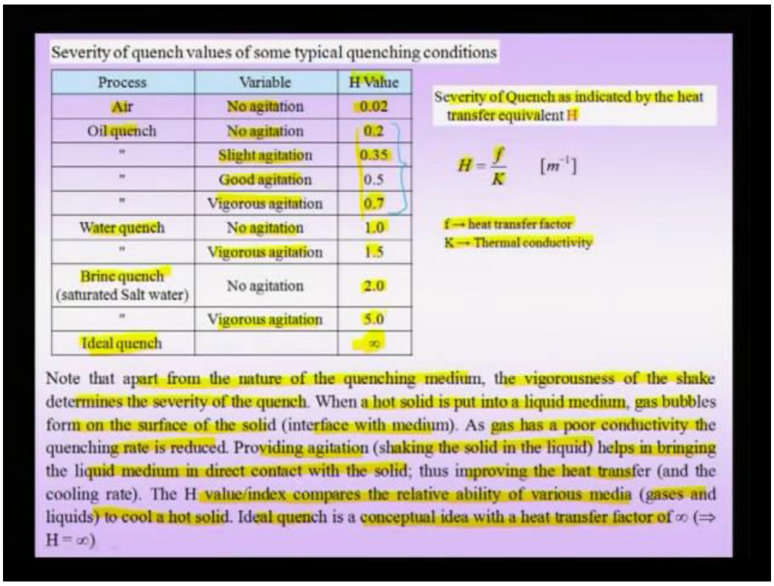

Severity of quench values of some typical quenching conditions

Process	Variable	H Value
Air	No agitation	0.02
Oil quench	No agitation	0.2
"	Slight agitation	0.35
"	Good agitation	0.5
"	Vigorous agitation	0.7
Water quench	No agitation	1.0
"	Vigorous agitation	1.5
Brine quench (saturated Salt water)	No agitation	2.0
"	Vigorous agitation	5.0
Ideal quench		∞

Severity of Quench as indicated by the heat transfer equivalent H

$$H = \frac{f}{K} \quad [m^{-1}]$$

f → heat transfer factor
K → Thermal conductivity

Note that apart from the nature of the quenching medium, the vigorousness of the shake determines the severity of the quench. When a hot solid is put into a liquid medium, gas bubbles form on the surface of the solid (interface with medium). As gas has a poor conductivity the quenching rate is reduced. Providing agitation (shaking the solid in the liquid) helps in bringing the liquid medium in direct contact with the solid; thus improving the heat transfer (and the cooling rate). The H value/index compares the relative ability of various media (gases and liquids) to cool a hot solid. Ideal quench is a conceptual idea with a heat transfer factor of ∞ (⇒ $H = \infty$)

Now, we have we said while we talked about quenching that actually we have various severities of quench well within a class for instance. Suppose, I could be talking about quenching in water, but that does not represent the single quenching rate, but actually could represent multiple quenching rates. Now, the various quenching process with an severity of quench as measured by a value called the H value.

The H is defined or the H of the severity of quench is indicated by the heat transfer equivalent of H which is given by H is given as f by K where, f is the heat transfer factor and K is the thermal conductivity. In other words H measures that how efficient is a quenching medium in removing heat and ideal quench is considered when you have the H value of infinity. That means, that is the perfect you would like to aim any other process would have a H value which is lower. Air quenching with no agitation gives you H value 0.02, oil quenching with again no agitation can give you a 0.2 cooling rate; that means, it is an faster cooling rate.

If you use sight agitation the H value increases; that means, now you are extracting heat better from the material by agitating it slightly. You can also do increasing amount of agitation to obtain a H value of 0.7, this implies for a single quenching medium like oil.

You can actually obtain a range of cooling rates or what you might is the cooling rates being indicated by the H value by actually either holding the sample still or by actually agitating at various rates. Now a few points have to be noted in this regard; that means, that apart from the nature of the quenching medium, the vigorous of the shake determines the severity of the quench.

That means, I can increase the severity of quench by shaking the material, when a hot solid is put in a liquid medium gas bubbles form on the interface of the solid. This may happen and this gas bubbles which are present on the interface of the medium, can actually deteriorate the heat extraction process. This is because the gas is a poor thermal conductivity and therefore, the quenching radius produce locally especially were the gas bubble is present.

Providing agitation; that means, shaking in the solid liquid helps in brining the liquid medium in direct contact to the liquid thus it improves the heat transfer and the cooling rate. The H value or index compares the relative ability of various media; that means, the middle the table we are seeing above; that means, gases and liquids to cool a hot solid. Of course, the we have already seen that the ideal quench which is the right at the bottom here with an H value of infinity is a conceptual idea with heat transfer factor of 100 infinity.

So, this is an important point to note that even though I expect a certain medium to cool at a very fast rate formation of gas bubbles can impede this process especially very locally were the gas bubble is forming. Therefore if I agitate the solid or equivalently agitate the liquid what might happen that the medium can come in direct contact with the substance or the material for instance steel. In this case and therefore, give you a higher cooling rate again in the same case with water quench that if I do not agitate I get a lower H value while if I vigorously agitate I can get an higher H value.

In the case of even oil quench we had seen that we can actually increase the H factor to a by a factor of 3 or more by vigorous agitation. More than water quench you can even obtain higher quenching rates by using brine quench; that means, you take water in which salt has been dissolved and we can get the higher quenching rate. And even in brine if you do vigorous agitation you can get a H factor up to 5.

So, the message of this slide is that often when we talk about water quench or oil quench or even air cooling, we have to specify if the medium or the substance is being agitated because in this case the overall heat transfer coefficient. That means, suppose I am keeping a substance, I am blowing air on it via fan in air. Then I get a better heat transfer coefficient or a better heat removal from the material and therefore, I get a better quench on the inside the material.

And I can use different media apart from oil quench and water quench like brine quench and to get a better cooling rate and there are other specialized media also which you can use. Of course, we have to note that in these cases we are assuming that the quenching medium is at room temperature, but of course, you can also keep the quenching medium below room temperature.

You can even go to cryogenic temperatures if for instance if the M F temperature for a certain substance is below room temperature. Then you need to cool the substance below room temperature, so that you can produce full martensite. So, these are some details of the quenching medium and the kind of heat treatment you need to carry.

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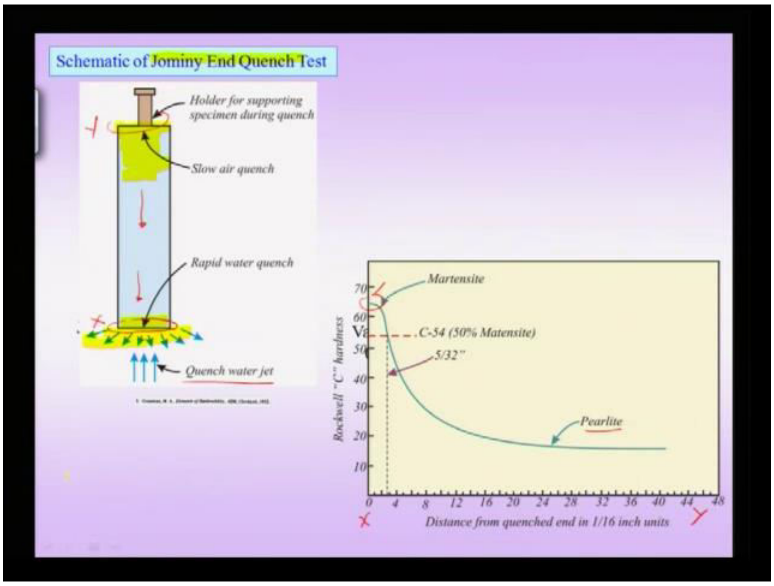

Schematic of Jominy End Quench Test

The standard test to find out hardenability of a material is via a what is known as a jominy end quench test in which case you take a cylindrical specimen. You throw a water jet at the bottom, so this end of the specimen is being cooled by water jet. The other end of the specimen is being only cooled in the open air, so the all the heat which is being extracted from the bottom. Therefore, the heat has to flow from top to bottom, in other words the heat has to flow in this direction.

So, this end of the specimen directly fills a quenching medium while this end is only being air cooled. And therefore, heat has to flow from top to bottom and we removed by this water jet. Now, such a quench produces martensite on the surface of this material. So, if you compare this and suppose this is my x point and this is y point. So, wherever this x is you have a high hardness due to presence of martensite while the other end y is low in hardness because there you only are producing pearlite.

And you would like to know where you produce 50 percent martensite and this you can do by actually cutting the specimen and polishing it. So, what you can do is that you can take your cylindrical specimen.

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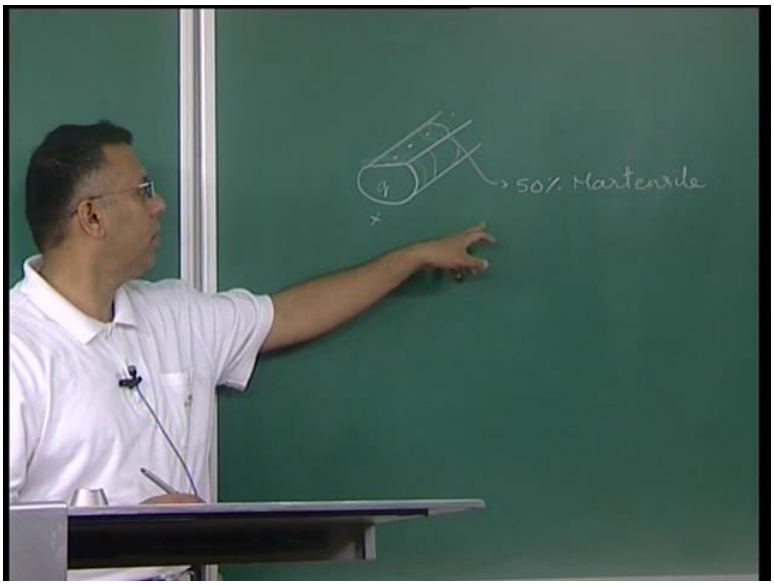

So, this is my cylindrical specimen, so I remove a certain section from the tops that I have a flat top. And now what I can do is that I can measure my hardness from say this is my quench end which I have marked as x and I can take hardness of various points along the cylinder. And I can plot it further I can also see using metallographic studies at which section am I producing for instance 50 percent martensite. So, by using a combination of hardness and metallographic studies I can find out the variation in hardness and also locate the region at which I can get 50 percent martensite.

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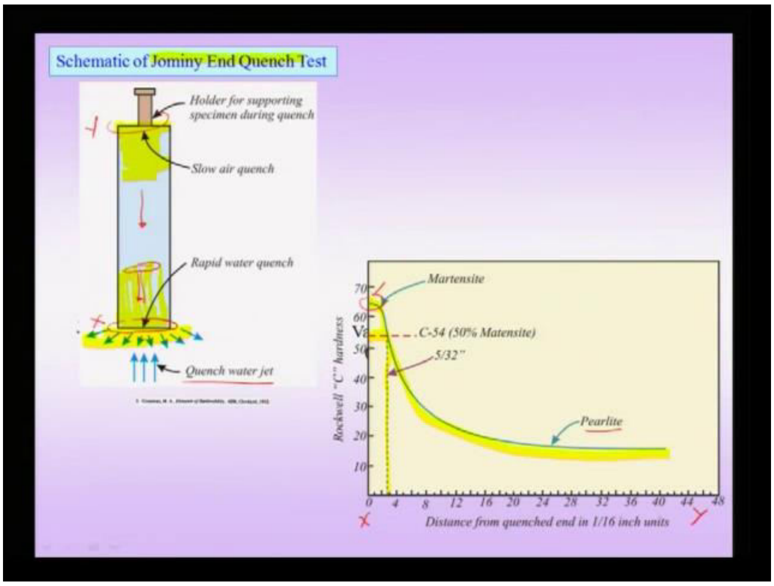

Schematic of Jominy End Quench Test

So, this is how the plot of the hardness is expected to look, you have a decrease in hardness along with the change in microstructure. And at certain distance you can actually produce 50 percent martensite. We are not considering the details of this jominy end quench test, but this can also tell you how hardenable in the material is a more hardenable material would you can actually harden to a larger distance as compared to a less hardenable material.

Because, as we have pointed out that the heat transfer from a section some were here is dependent on the heat thermal conductivity towards the bottoms. That means it is heat is being conducted through the material and this is not in direct touch with the quenching medium.

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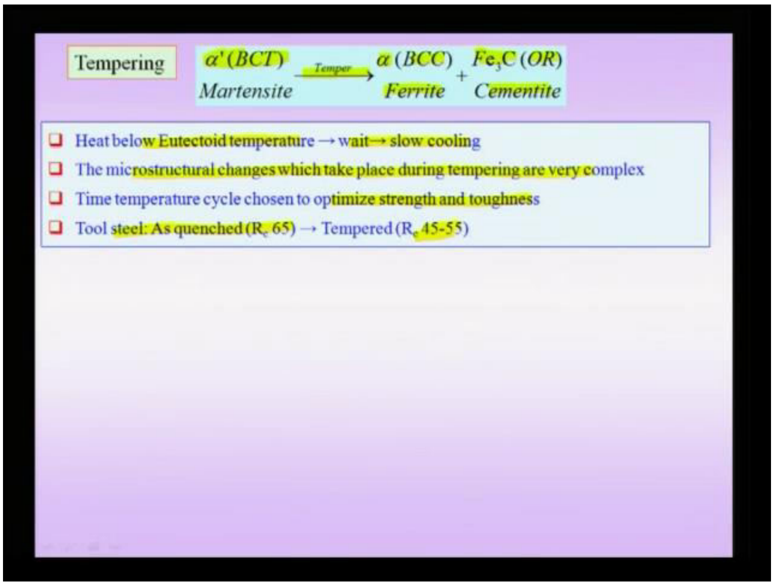

Tempering

$$\underset{\text{Martensite}}{\alpha'(BCT)} \xrightarrow{\text{Temper}} \underset{\text{Ferrite}}{\alpha(BCC)} + \underset{\text{Cementite}}{Fe_3C\,(OR)}$$

- ☐ Heat below Eutectoid temperature → wait→ slow cooling
- ☐ The microstructural changes which take place during tempering are very complex
- ☐ Time temperature cycle chosen to optimize strength and toughness
- ☐ Tool steel: As quenched (R_c 65) → Tempered (R_c 45-55)

As I pointed out this quenching treatment has to be followed by a tempering treatment. So, that we can get a combination of ductility and strength; that means, we can optimize strength and toughness and toughness being the area under the curve in a tensile test or suppose you are wanted to do an impact test then it is the energy absorbed during impact. So, during the tempering process the body centered tetragonal structure of martensite which is represented as alpha prime tends to go back to its equilibrium state.

And the equilibrium being given by the phase diagram because this alpha prime is a meta stable state. The equilibrium phases being alpha and F e 3 C, F e 3 C been orthorhombic alpha being B C C; that means, a solid solution of carbon in iron, so you have a product of ferrite and cementite when you temper martensite. Of course, you do not allow all the martensite to be converted into ferrite and cementite, you only do it.

So, as to get the optimum combination of strength and ductility, so you heat below the eutectoid temperature and weight and then after that slowly cool the sample. The actual micro structural changes taking place during this tempering are very complex. And we are not considering them in detail here, but certain specialized text in this area would help you. Tool steel for instance as quenched is about 65 R c, but we can temper it to get a R c value which is a Raquel c hardness value of about 45, so that or 55, so that this can be used in actual service. So, typically hardening processes are followed by tempering process, so that you can get a combination of ductility and strength.

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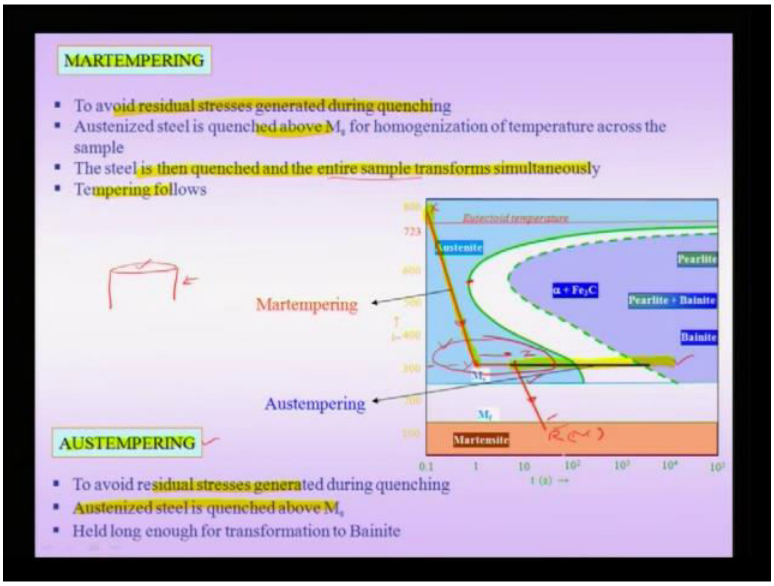

MARTEMPERING

- To avoid residual stresses generated during quenching
- Austenized steel is quenched above M_s for homogenization of temperature across the sample
- The steel is then quenched and the entire sample transforms simultaneously
- Tempering follows

AUSTEMPERING

- To avoid residual stresses generated during quenching
- Austenized steel is quenched above M_s
- Held long enough for transformation to Bainite

There are certain variations of this process which can actually give you certain benefits with regard to residual stresses. And the 2 important process which are used 1 is called mar-tempering other is called aus-tempering. Now, of course, we are using a single master curve to study all this, but we have to note that since this also involves cooling steps, this is an extension of the standard T T T diagram. Now we do mar-tempering to avoid residual stresses generated during quenching.

Now what we do is that the austenite steel is quenched just above M s, so we take the steel austenite is a austenizes at a high temperatures. Then we cool it along the red line actually the red line is overlaid on the blue line. So, for now we will focus on the red line we hold it bring it down just above the M s temperature and then we allow the sample to homogenize in temperature because when we do a normal quench. For instance suppose I take a cylindrical sample and quench it the surface faces the quenching medium.

And; that means, that this is cooled and the interior is not cooled and in this process residual stresses are generated. This is residual stresses are the thermal residual stresses which is in addition to the residual stresses produced directly due to the transformation itself. So, after this temperature homogenization hold which is from here to here. So, that I hold it, so that my entire sample is now homogenized temperature. And now of course, the sample itself is pretty cool and from here I quench.

Now to cross the m martensite start and martensite finish lines, so that finally, I produce a martensite uniformly across. And this is important because the steel is now quenched such that the entire sample transforms simultaneously. So, this is a slight variation in the quenching processes and this heat treatment cycle now involves a quench region say for instance I can label this x y. So, I start from the x point quench it to y point then I go to Z and then quench it to room temperature.

So, therefore, doing the x y's I am cooling it to avoid the nose of the T T T diagram. Then I hold it above the M s temperature. So, that still we are in the gamma phase field, but we are not allowing any transformation what we are allowing is that the entire sample is brought to a same temperature. And then further we quench it, so that the residual stresses produced in the martensite are small. And that implies that the cracks quench cracks which are produced this residual stresses which is building up in the material is small and which is good for in service applications.

So, finally, of course, we quench the material from Z to R to produce full amount of martensite. In aus-tempering which is another variation and this again is designed to avoid residual stresses generate during quenching. We the austenized steel is quenched above M s again like before you follow the x y part of the curve. Then we do not then after crossing Z, we do not quench, but we hold it isothermally to a, so as to produce a final structure which is Bainite. So, in the mar-tempering process we are producing martensite and avoiding residual thermal stresses.

In aus-tempering we are again holding the austenite just above the M s temperature, but isothermally holding is to finally, produce the Bainite which is as we know. Since, we are now working at very low temperatures we know that it will be a very fine Bainite which is produced and which will be which will have reasonably good strength and which is good for applications.

So, now, we have considered two variations of the quenching process and these 2 have been designed specifically to reduce the residual stresses which arise during quenching. 1 is mar-tempering and other is aus-tempering and also we have seen that how the T T T diagram can be used as an important engineering application to design these heat treatments specifically the once we have just now seen. So, wherein we have used a specific shape of the T T T nose; that means, we avoid the nose, but then we know that there is more time available below the nose.

So, I can hold my sample in this region which is I have shown by circle and therefore, precise shape of the T T T diagram. T T T diagram is being used to design my heat treatment, so as to produce product which is not only is hard, but often is as a combination of hard hardness and toughness, but also is low on residual stresses which could lead to ((waring)). Even in the case of martensite it is needless to say we would like to do some tempering later on to increase the overall toughness of the material.

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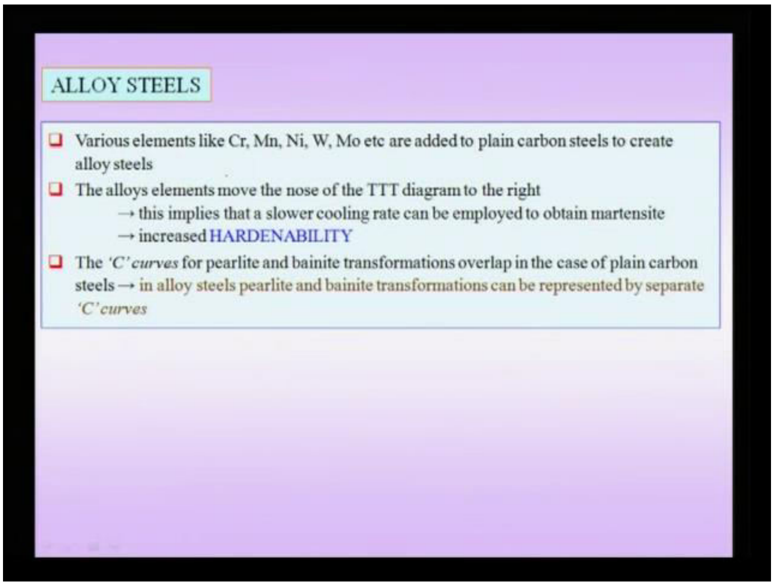

ALLOY STEELS

- ❑ Various elements like Cr, Mn, Ni, W, Mo etc are added to plain carbon steels to create alloy steels
- ❑ The alloys elements move the nose of the TTT diagram to the right
    - → this implies that a slower cooling rate can be employed to obtain martensite
    - → increased HARDENABILITY
- ❑ The *'C' curves* for pearlite and bainite transformations overlap in the case of plain carbon steels → in alloy steels pearlite and bainite transformations can be represented by separate *'C' curves*

Now, the next topic we would like to consider is alloy steels.