

Structure of Materials
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Lecture - 41
Chapter-08
Phase Transformations

Let us next look at Continuous Cooling Transformation diagrams, otherwise known as C T diagrams.

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Continuous Cooling Transformation (CCT) Curves

- ❑ The TTT diagrams are also called Isothermal Transformation Diagrams, because the transformation times are representative of isothermal hold treatment (following a instantaneous quench)
- ❑ In practical situations we follow heat treatments (T-t procedures/cycles) in which (typically) there are steps involving cooling of the sample. The cooling rate may or may not be constant. The rate of cooling may be slow (as in a furnace which has been switch off) or rapid (like quenching in water).
- ❑ Hence, in terms of practical utility TTT curves have a limitation and we need to draw separate diagrams called Continuous Cooling Transformation diagrams (CCT), wherein transformation times (also: products & microstructure) are noted using constant rate cooling treatments. A diagram drawn for a given cooling rate (dT/dt) is typically used for a range of cooling rates (thus avoiding the need for a separate diagram for every cooling rate).
- ❑ However, often TTT diagrams are also used for constant cooling rate experiments—keeping in view the assumptions & approximations involved.
- ❑ The CCT diagram for eutectoid steel is considered next. Blue curve is the CCT curve and TTT curve is overlaid for comparison.
- ❑ Important difference between the CCT & TTT transformations is that in the CCT case *Bainite cannot form*.

We had already noted the T T T diagrams are drawn for isothermal holding conditions that means, we these are representative of transformation times under isothermal hold treatment. And we had also noted that under practical circumstances, we have heat treatments that means, we follow certain things known as time temperature cycles or time temperature procedures in which typically, there are steps involving cooling the sample. That means, that there are treatments of course, where you might isothermally hold, but the there may be steps within the time temperature cycle within the heat treatment cycle, wherein you may actually cool the sample.

The cooling rate may or may not be constant that means, the cooling rate itself could change during the process. The rate of cooling may be slow like for instance we may leave a sample inside the furnace and allow the sample to cool along with the furnace

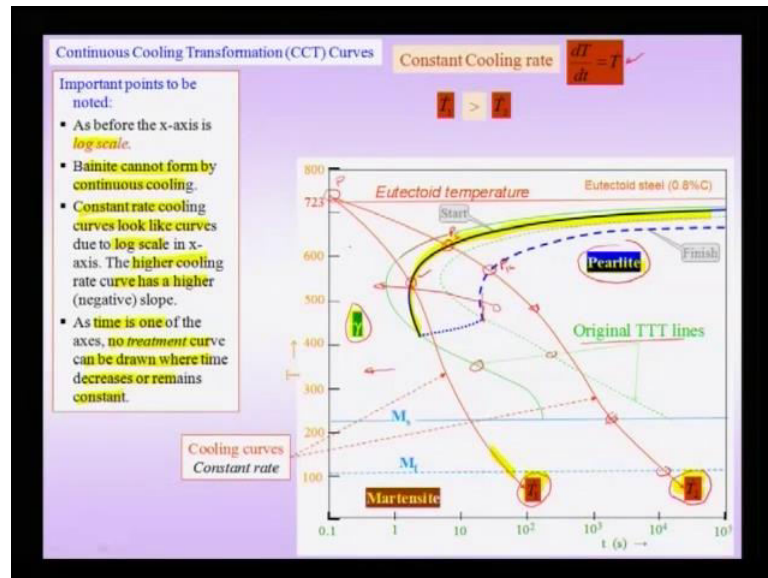
which takes a long time. In other words the cooling rate will be small or we may take the sample and put it into water, which we call quenching in water.

In which case my cooling rate obtained is high, sometimes of course we will see in coming examples, that we actually take a melt and cool it at even much higher rates than that allowed by quenching in water. So, in practical terms T T T diagrams have the limitation and we have to draw a separate set of diagrams called the continuous cooling transformation diagrams or C C T diagrams. Wherein transformation times and of course, whenever we are talking about transformation times, we include the products obtain and the microstructure, which we overlay on these diagrams are noted using constant cooling treatments and not constant temperature treatments.

A diagram drawn for a given cooling rate for instance i use a $d T$ by $d t$ which is approximately constant is typically, used for a range of temperatures or a sorry, a range of cooling rates. This avoiding the need for a separate diagram for each cooling rate, that means, though I may have a T T T diagram, which is only valid for a certain range of cooling rates, I may or strictly speaking for just one cooling rate, which is held constant, I may use it for a range of cooling rates around that cooling rate. And often you would note that T T T diagrams are also used for cooling rate experiments. But in such circumstances, we have to keep in view the assumptions involved and the approximations, which underlay the drawing of those T T T diagrams.

C C T diagram for eutectoid steel is we will talk about next and we will overlay on the C C T diagram also the preexisting T T T diagram. So, that we know the 2 for comparison, the important difference for the eutectoid steel is the difference that for the C C T, that means under cooling treatments bainite cannot be formed.

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So, this how the CCT diagrams looks and the curves, which correspond to the TTT diagram or the original TTT diagram, are drawn in green color. So, these are my original TTT curves, which are here. So, it is my original TTT curves, which are both these ones, this for the start and this one for the finish and the current CCT curves are the ones drawn in blue. So, this is my start line and as you would note that 2 products having marked in this diagram, the martensite which is obtained at high cooling rates and the pearlite, but there is no bainite.

So, again like before my starting point is of course, my austenite and I am cooling the austenite using a constant cooling rate like and this constant cooling rate $\frac{dT}{dt}$ as shown in the right hand side here, could be which is represented as \dot{T} that means, this $\frac{dT}{dt}$ temperature per time is represented as \dot{T} and we can use cooling rate, which is increasing.

For instance in this case, there are 2 cooling curve shown one with \dot{T}_1 , which is greater than a slower cooling rate, which is \dot{T}_2 . Both these \dot{T}_1 and \dot{T}_2 are constant cooling rate curves. A few important points, we will note before, we describe this diagram in detail, we have to note that this x axis as before is in a log scale bainite cannot form by continuous cooling. Constant rate cooling curves look like curves, I mean they are not straight lines, but they are curves in this plot, because of this log scale used along the x axis.

And an higher cooling rate curve typically, has the higher slope as and this slope is negative of course, as compared to a slower cooling rate that means, T 1 dot is a fasted cooling rate as compared to T 2 dot. And this straight line and if you had plotted, normal temperature versus normal time, we would have obtained a straight line, but because the x axis is a log scale, we see that these curves start to loop. They are not straight, but they are curve. And as before no treatment curve can be drawn, where the time decreases or remains constant, we know the time always has to flow in the positive direction.

Therefore, we should not draw any curves for instance, I am not allowed to draw a curve on this, which goes say for instance like this here. Further more I am not even allowed to draw curves like these on this. For instance because, in such a case my starting point is in the pearlitic phase field and for drawing all T T T diagrams for eutectoid steel, we have noted that we are interested in the eutectoid transformation. That means, that my starting phase has to be the gamma phase, which is my austenite and I study the transformation of this gamma in 2 various alphas plus f e 3 c or the martensite, which are the 2 possible micro constituent surfaces or the microstructures obtained after this transformation.

So, when I cool my sample say using a slow cooling rate like T 2 dot, then I obtain that I start with of course, my above 7 23 degrees as my austenite, then on cooling i obtain a final product, which is pearlite. Once the curve of course, has crossed a curve like this here and here I have started with pearlite, start and this means pearlite start and this would be my pearlite finish. And that means, whole of my gamma has got transformed into pearlite and therefore, these intersections here right here have no meaning.

So, this we should not read into these intersections at this point all the starting product has transformed into pearlite, which is a micro constituent and therefore, no further transformation of this pearlite can take place. on the other hand suppose I look at a curve like T 1 dot in which case the cooling rate is faster, I see that I start again with this point, which is the above the eutectoid temperature say the point p. Though I hit my start curve for formation of pearlite, but I do not cross the finish curve the finish curve.

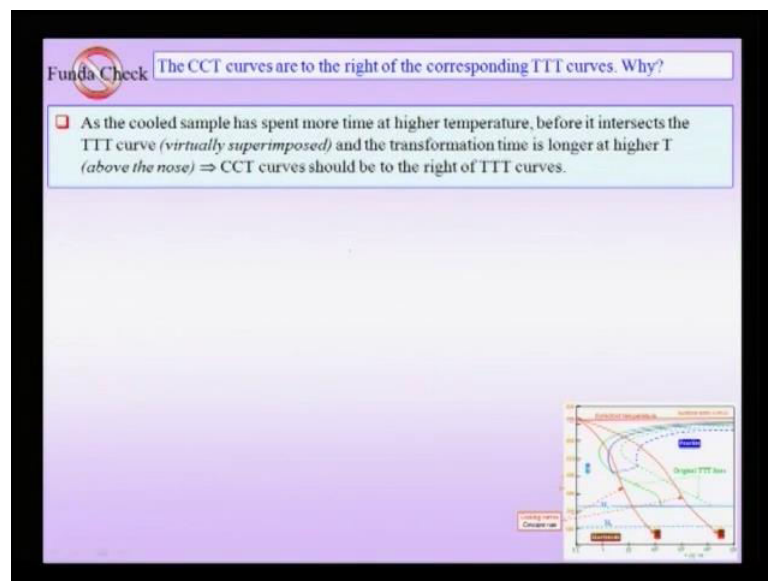
For pearlite is here this line and I do not cross this line, but I only hit the start line, that means, i land up with microstructure, which is pearlite and the remaining austenite can transform into martensite therefore, I have a combination of phases now. And of course, I can avoid the nose of the C C T diagram and therefore, go to higher cooling rates in

which case, I will obtain a fully martensitic phase right here. So, I you can use a cooling rate which, we will see in the next coming slides.

So, to summarize this slide here, I have my T T T diagrams C C T diagrams, which have been overlaid on the T T T diagrams. The green curves are my original T T T diagrams, the blue curves are my new C C T diagrams. If I use constant cooling treatments even though, I am using a constant rate of cooling $t \dot$ like $T \dot 1$ or $T \dot 2$, which is nothing, but $t \dot T$ by $d t \dot d$ capital T by d small t. These curves these straight lines start to be look like curves, because now time is in log scale then further more I have noted.

That if you completely transform all the gamma into say for instance pearlite, then further intersections of this curve with for instance say martensite start of the martensite, finish lines have no significance. And the most important thing to reiterate, there is no bainite formation possible in a constant cooling, when you look at these curves you notice that the blue, curve is shifted with respect to the green curve.

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So, I will we can ask this question why is the C C T curves to the right of the corresponding T T T curves that means, why does it take longer time for instance to form.

now actually I have to talk about since I am using cooling hit, I have to actually talk about intersection with the C C T curve and not the T T T curve. The transformation time is longer at higher temperatures, we know this from the curves that, if i go to higher and higher temperatures before the nose.

Then I note that, it takes longer and longer time for me to the transformation to take place and since the sample though is intersecting actually, the curves in this region, but it has spent more time at a higher temperature, where the transformation times are longer. This is above the nose of course, this means C C T curve should be the right to be has to be to the right of the T T T diagrams and that is how it has been drawn.

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Common heat treatments involving cooling

- Common cooling heat treatment labels (with increasing cooling rate) are:
Full anneal < Normalizing < Oil quench < Water quench
- The microstructures produced for these treatments are:
 - > Full Anneal (furnace cooling) → Coarse Pearlite
 - > Normalizing (Air cooling) → Fine Pearlite
 - > Oil Quench → Martensite (M) + Pearlite (P)
 - > Water Quench → Martensite
- To produce full martensite we have to avoid the "nose" of the TTT diagram (i.e. the quenching rate should be fast enough).
- Within water or oil quench further parameters determine the actual quench rate (e.g. was the sample shaken?).

So, now we have introduced a new tool, which is now my C C T diagrams, which has important practical applications as we shall see now. And therefore, I can use these C C T diagrams in what we might call heat treatment cycles or heat treatment applications where in we want to say for instance start with eutectoid steel and produce microstructures with various hardness or various strength.

Now the common cooling treatments and typically the labels used or the names used for these are full annealing, normalizing, oil quench and water quench. And these have been arranged in the increasing order of the cooling rate for instance water quench has the highest cooling rate, next is lower is oil quench normalizing is even lower and annealing treatment is even lower.

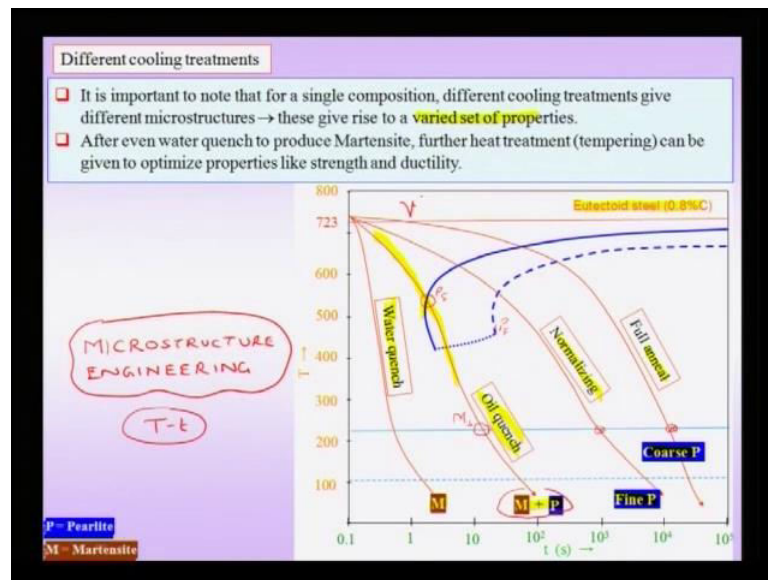
And the typical microstructures produced for these cases are, when you do full annealing like for instance by using a furnace cooling treatment, you get coarse pearlite. If you would use a normalizing treatment, which is for instance what we call air cooling, that means, you take the sample out of the furnace and leave it in open air. And you do not do any further thing to it, we obtain typically a fine pearlite. If you quench it in oil, we can produce a mixture of martensite and pearlite and if you quench it in water, we can produce pure martensite.

And we will draw the corresponding cooling curves for all these are in the coming slides on the C C T diagrams. To produce full martensite, we have noted that we have to avoid the nose of the T T T diagram or to more precise I can now, we since that we have introduced C C T diagram. So, I can call this is the C C T diagram. So, we have the C C T diagram and I have to avoid the nose of the C C T diagram and that means, that I have to my quenching rate has to be fast enough.

Once I avoid the nose of the C C T diagram, then I can produce the sample in which all the sample is transformed into martensite. But of course, we have to keep in mind that in all practical situations there might be some amount of retained austenite. That means, all the martensite might not have transformed into all the austenite might not have transformed into martensite and we may have some residual amount of austenite, which is called retained austenite.

Now here in naming these treatments like water quench oil quench normalizing etcetera and also noting the quench rate, we have made some simplifications. And there are further parameters, which we need to take into account to actually determine how the quench rate changes within a particular treatment, which we will take up in one of the coming slides.

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So, let us overlay now the different cooling treatments on top of the CCT curve. So, for instance the highest cooling rate is for the water quench here, in which case I avoid the nose of my CCT diagram and I produce a full martensite structure and to reiterate some amount of retained austenite might be present in practical situations.

If you use a slightly higher cooling rate, slightly lower cooling rate, which is produced by given by an oil quench that means, I take my sample out and put it inside an oil. Typically, there are special oils for this purpose, which will give you a high cooling rate, but not as high as water quench, then I can produce the microstructure, which is a combination of martensite and pearlite because, now you started your pearlitic transformation, but this pearlitic transformation was not completed and the remaining.

So, this is where my pearlite started, but then it was not completed you never hit this curve, which is the pearlite finish curve. Therefore, what happens is that the remaining austenite transforms into martensite, when you hit the martensite start curve. And therefore, you have a microstructure which consists of martensite plus pearlite. Now suppose you have a even lower cooling rate as I mentioned by leaving a sample outside the furnace then you can produce a fine pearlitic structure or if I use a even lower cooling rate, which is called annealing treatment or a full annealing treatment in which case I leave my sample inside the furnace allow the furnace to slowly cool.

Then I can obtain a coarse pearlitic structure and as I again pointed out this coarse pearlitic structure of course, we will note the properties very soon, but we have to note again that in the case of normalizing and full annealing. These intersections have no meaning. So, these intersections should not be given any importance. Now the important thing of course, is that the whole heat treatment, which we are studying here is that for a single composition.

And now we are talking about eutectoid steel or a 0.8 percent carbon steel, I can produce different microstructures and of course, we have seen certain micro constituents being part of it like pearlite. And these different microstructures can give rise to a varied set of properties that means, what I am doing here should be technically called microstructure engineering and I am using microstructure engineering.

So, let me write this in bold because, one of the important ways of defining materials engineering is that materials engineers give lot of importance to microstructure engineering. And this is true not only for mechanical properties, but also for certain magnetic and many other properties. So, what we are doing is microstructure engineering.

So, I have here a handle on the properties by doing not changing the composition that means, I have eutectoid steel, but I vary my heat treatment, which means I vary my temperature time cycle. So, as to get a varied set of properties and these varied set of properties are obtained because, for each one of these heat treatments I produce a different microstructure.

So, I have a handle on the properties not via the composition, but via the microstructure which is controlled by heat treatments and of course, here we are considering some simple uniform heat treatments. But in real life you may use a combination of heat treatments and further I may use, what is might called thermo mechanical treatments in which case not only I am using temperature cycles, but also I am giving mechanical deformation.

In which case I have further control over the final properties I obtained the microstructure etcetera. So, here we have seen that in this that I can use different cooling treatments, starting from austenite, the starting phase gamma, the gamma phase field and by giving different cooling treatments I can get different microstructures, which can be a


full martensite. Martensite plus pearlite fine pearlite or coarse pearlite and I can get different properties, which we will see in the coming slides.

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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	10^3
Melt-Spinning	$10^6 - 10^8$
Evaporation, sputtering	10^9 (expected)

* Depends on conditions discussed later



Now, we have to note that, what are the typical cooling rates of various process. Now we have said that for instance, typically noted that water quench has a higher cooling rate as compared to oil quenching, which is a higher rate compared to air cooling and furnace cooling we said that was the slowest cooling rate. So, what are the typical cooling rates and here of course, we are noting it in terms of Kelvin per second or degrees Celsius per second, because these both are equivalent.

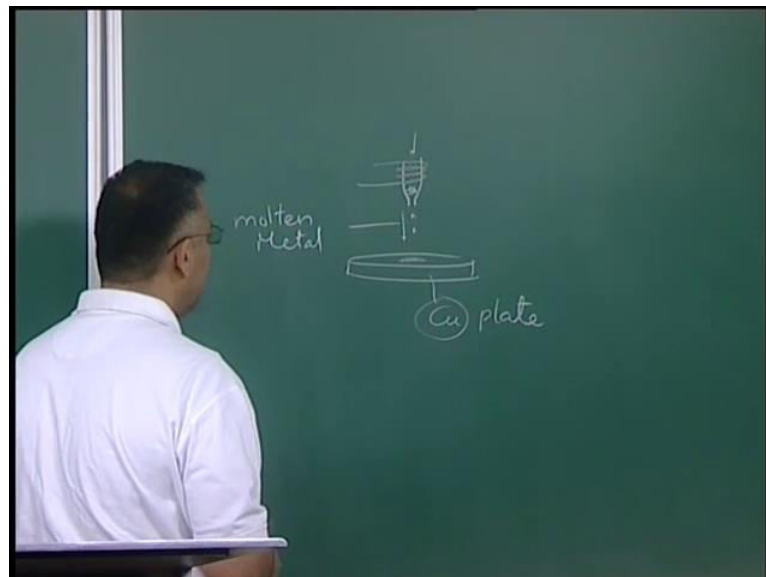
So, I could also use a unit different unit here which is degrees Celsius per second. So, on the low end of course, is my furnace cooling in which case I obtain a cooling rate, which is order of $10^{\text{power minus } 5}$ to $10^{\text{power minus } 3}$ Kelvin per second. Air cooling can give you 1 to 10 degrees per second cooling rate that means, the sample would fall at a fastest rate above 10 degree Celsius per second.

And now of course, we have to note and we will pay more attention to it in the coming slides, that what we are talking about the cooling rate is the surface cooling rate. Because, the quenching medium or the medium is not in direct touch with the interior of the material and therefore, what we can the medium has access to is only the surface. And therefore, suppose I had a sample for instance a cylindrical sample what I am talking about is the cooling rate on the surface.

So, suppose this is my sample, I am monitoring the cooling rate on the surface here. So, this is my cooling rate and not at the bulk or the interior, where the cooling rate could be different, which is determined which is out of control by the conductivity. Oil quenching can give you an higher cooling rate of the order of about 100 degrees Celsius per second, water quenching even higher about 500 degrees Celsius per second. And these 2 stars indicate that there are further details involved, which we will come in the consider in the coming slides.

There is a there are further techniques like splat quenching and I will go to the board to explain you what is splat quenching, in splat quenching we typically have a substrate of high thermal conductivity.

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For instance you may have a copper substrate and you can put a molten pool of material say for instance a molten, you could melt using induction some metal and you can purge it with argon and this molten pool of jet could fall on the strain and get flatted out. So, this is. So, when this molten metal falls on the substrate of copper for instance, which is a high thermal conductivity, then very high cooling rates are experienced by especially this is how the initial surface which is falling on the sub state.

And since the amount of metal being poured put here is very small typically, most of the metal fields had very high cooling rate. So, this is my splat quenching technique and


there are variations which are called gun quenching, where in the velocity of the jet can be very high. The molten pool can be very high.

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What are the typical cooling rates of various processes?

Process	Cooling rate (K/s)
Furnace cooling (Annealing)	$10^{-5} - 10^{-7}$
Air Cooling	1 - 10
Oil Quenching*	~100
Water Quenching*	~500
Splat Quenching	10^3
Melt-Spinning	$10^6 - 10^8$
Evaporation, sputtering	10^9 (expected)

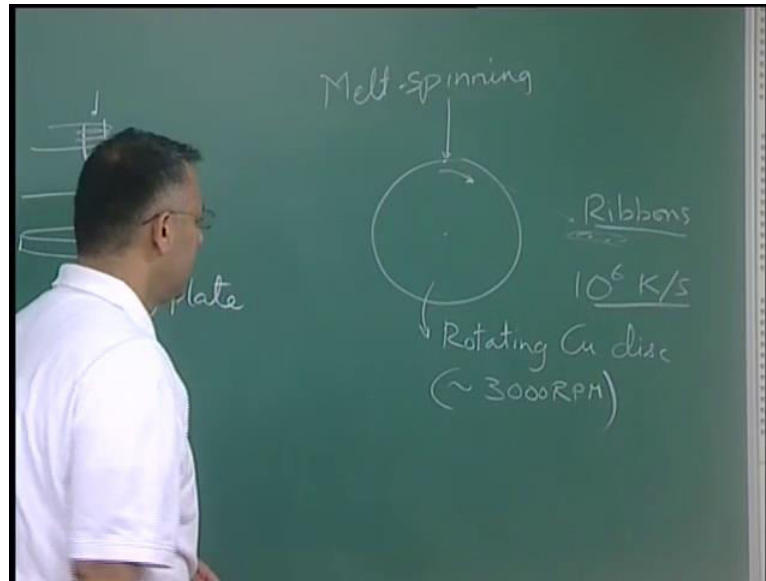
** Depends on conditions discussed later*



Handwritten note: °C/s

And i can obtain cooling rates of the order of about 10^5 Kelvin per second of course, measurement of this cooling rate that how do you obtain such a high cooling rate, itself is a challenging task and typically, some micro structural features could be used for that. Now even higher cooling rate is obtained by a process known as melt spinning and the and you can obtain cooling rates of the order of about 10^6 Kelvin per second and in melt spinning typically, like unlike the splat cooling.

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What we use here again is a disc, rotating copper disc and disc rotating copper disc for instance and this rotation speed could be of the order of about 3000 R P M. 3000 revolutions per minute and we molten stream of metal would fall on this and since the wheel is rotating no single point would see a lot of metal falling on it. And therefore, and for instance you would form a foil which comes out of it. So, you will get a thin sheet which comes out of it and this sheet of course, most of it would have felt a very high cooling rate of the order of about 10 power 6 Kelvin per second.


So, this process is known as melt spinning and this process gives you ribbons. So, this is my rotating copper wheel on which I throw a jet of stream of metal and I can get very high cooling rates. Now and if, the cooling rate is very very high.

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What are the typical cooling rates of various processes?

Process	Cooling rate (K/s)
Furnace cooling (Annealing)	$10^{-2} - 10^{-1}$
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)

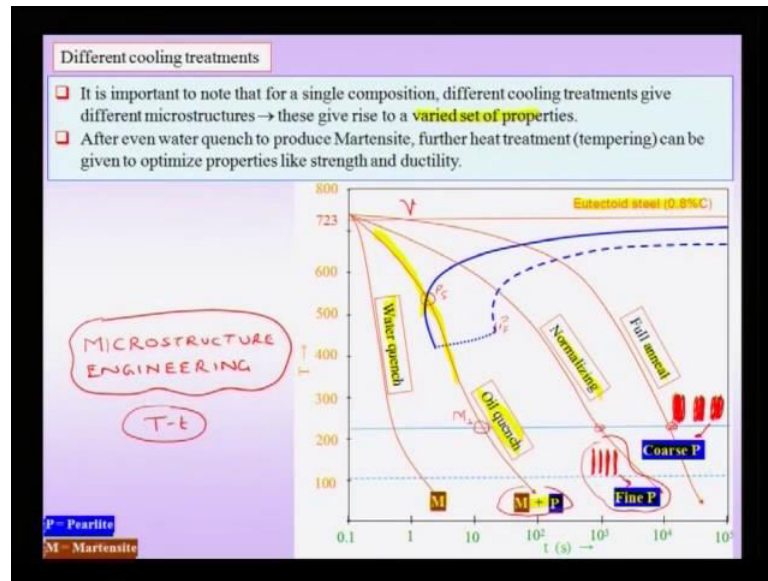
* Depends on conditions discussed later



In fact, you may not even obtain a for certain compositions, you will not even obtain a crystalline product you may obtain an amorphous product. For the even higher cooling rates have been reported for process like evaporation sputtering, which of the order of is above 10^9 Kelvin per second and of course, we should note that even at such high cooling rates for instance suppose, I take a metal like aluminum. It is difficult to amorphize aluminum even using such high cooling rates.

So, with me I have many processed with which i can use a different kind of a cooling rate increasing, cooling rate as you can see downward. And therefore, I can have a handle on the microstructure, which is produced. 2 things of course, not only that I can control the micro constituents like pearlite, but I can control the fineness of the pearlite.

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That means, if you look about talk about here. Suppose I am talking about fine pearlite here that means, my pearlite would consist of alpha and $F e_3 c$ which are finally, distributed like this. So, this is my fine pearlite, on the other hand in the case of course pearlite, I may obtain the wavelength of this course pearlite might be larger. So, this is my coarse pearlite and this is my fine pearlite and as you would expect that the fine structure has a higher hardness as compared to the coarse structure.

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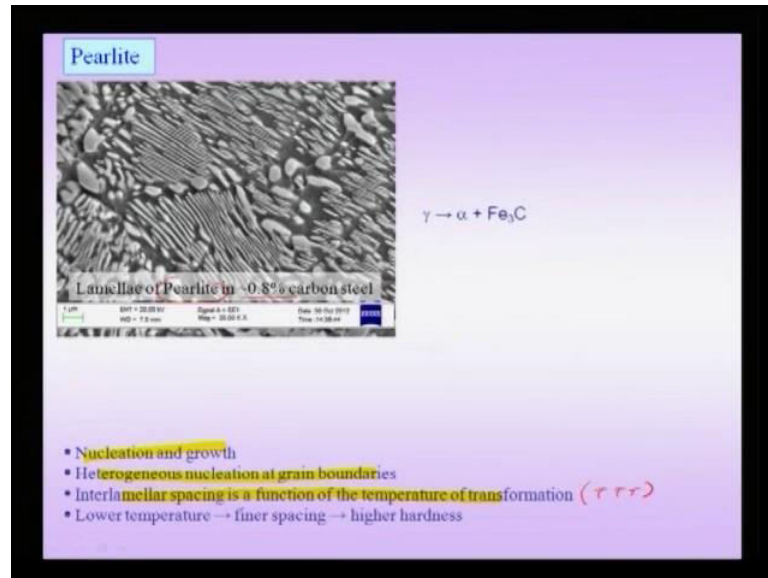
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So, I have a handle on the cooling rates and as we shall see later within oil quench and water quench, further we may control the parameters to a you know get a range of cooling rates.

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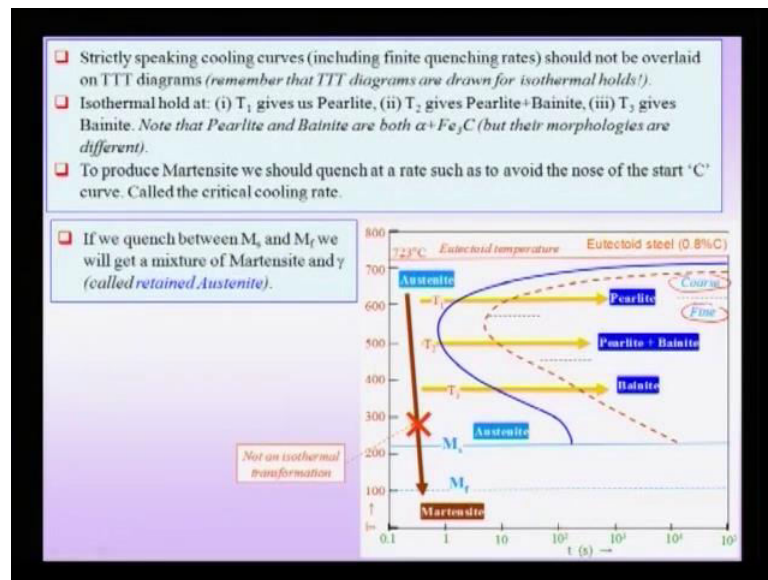


So, we have already seen this microstructure. So, let us talk a little bit more about what how would we obtain this pearlite and martensite and also bainite and what are the growth process involved or what are the issues involved in their phase transformation. So, we already seen that this pearlite consists of alternating lamella of alpha and Fe_3C and this is for now for an eutectoid composition.

This phase forms by nucleation and growth process and we will see that soon very soon and typically, it occurs by heterogeneous nucleation at grain boundaries. And the inter lamellar spacing is a function of the temperature of transformation or as we have seen of course, this is in the case of the T T T diagram. Because, I am talking about a T T T kind of scenario and suppose, I am talking about a C C T scenario, then I have to talk about the cooling rate.

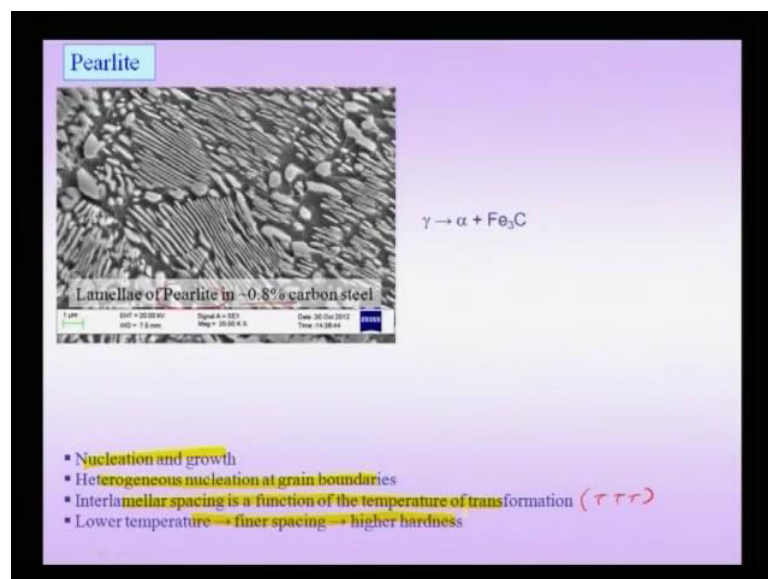
In other words we already seen a faster cooling rate gives you a finer microstructure and of course, similarly if you do the transformation at a higher temperature then you obtain a finer pearlite. Because, there is you might remember that, we actually did this sometime back that when we do the T T T diagrams.

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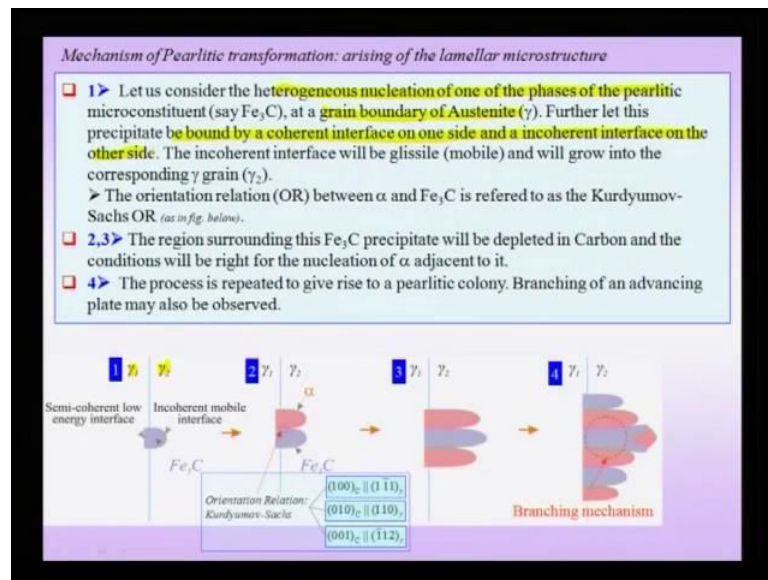
We had noted that at higher temperature we obtain the coarse pearlite and at lower temperature where the nucleation rate is expected to be higher, but the growth rate lower we obtain a fine pearlite.

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Now, the we have also noted that the finer spacing structure has a higher hardness of course, we are talking about the eutectoid transformation, which is gamma giving alpha plus F e 3 C.

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Now what is the mechanism by which this lamellar structure arises in pearlite. So, let us talk about heterogeneous nucleation at a gamma 1 gamma 2 interface. So, gamma 1 is 1 grain of gamma, gamma 2 is another grain of gamma and we are talking about heterogeneous nucleation in of one of the phases for instance pearlite at a grain boundary of austenite.

Let this precipitate be bound by a coherent interface on one side and an incoherent interface on the other side. Coherent interface is 1, where the planes are continuous across from one phase to the other and incoherent interface where there is not continuity of planes from one site to the other. So, this i can draw schematically here, suppose I am talking about phase 1 and I am talking about phase 2.

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I can talk about plains being continuous across these. Of course there might be distortion because, the lattice parameters may not be same, but plane atomic planes are continuous, if I talk about a in. So, this is my coherent interface, in an incoherent interface the atomic planes have no matching from one side to the other for instance this could be one set of atomic planes. The other set of atomic planes could be like this and there is no matching of planes from one side to the other.

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Mechanism of Pearlritic transformation: arising of the lamellar microstructure

- 1> Let us consider the heterogeneous nucleation of one of the phases of the pearlitic microconstituent (say Fe_3C), at a grain boundary of Austenite (γ). Further let this precipitate be bound by a coherent interface on one side and an incoherent interface on the other side. The incoherent interface will be glissile (mobile) and will grow into the corresponding γ grain (γ_2).
 - > The orientation relation (OR) between α and Fe_3C is referred to as the Kurdjumov-Sachs OR (as in fig. below).
- 2,3> The region surrounding this Fe_3C precipitate will be depleted in Carbon and the conditions will be right for the nucleation of α adjacent to it.
- 4> The process is repeated to give rise to a pearlitic colony. Branching of an advancing plate may also be observed.

Orientation Relation Kurdjumov-Sachs

$(100)_\alpha$	\parallel	$(111)_\gamma$
$(010)_\alpha$	\parallel	$(010)_\gamma$
$(001)_\alpha$	\parallel	$(112)_\gamma$

Branching mechanism

Now, an interface being coherent or semi-coherent as important consequences in terms of strain energy involved. It also has important chemical energy involved and a coherent interface has a lower chemical energy at higher strain energy. And also the important point to note is that, for instance suppose, I am having a semi coherent interface on this side and an incoherent interface on the other side for this gamma as the Fe₃C gamma interface. I would notice that the incoherent interface is more mobile or glissile as compared to the coherent interface.

And therefore, since the semi-coherent interface or the incoherent interface is more mobile or glissile as compared to the coherent interface or a semi-coherent interface then this side would grow as compared to the opposite side. So, therefore, I would have now the growth sorry, not this one the growth of the alpha Fe₃C in this direction. So, this growth direction will be more.

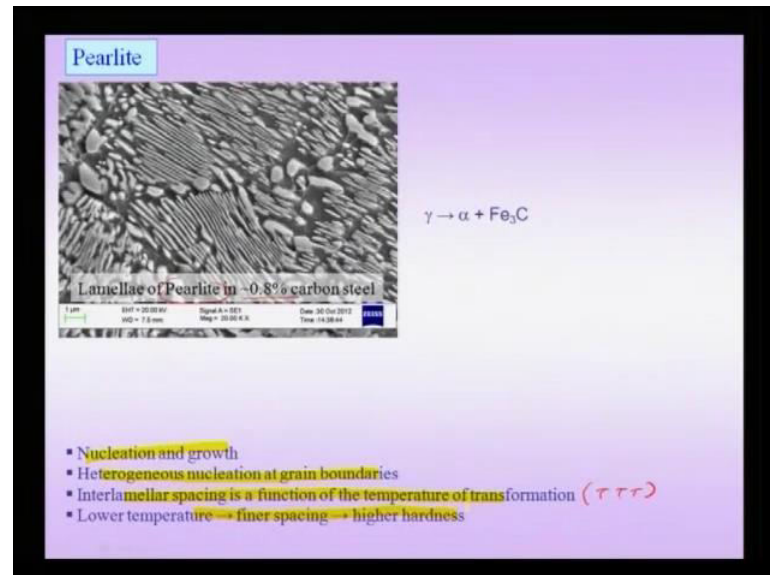
Now if Fe₃C grows then what happens is that, the region surrounding this Fe₃C precipitate will be depleted in carbon and the condition would be right for the nucleation of alpha adjacent to it. So, now, after this Fe₃C has gone some distance and the alpha could actually, nucleate next to it and actually grow. So, an alpha can nucleate and grow, this orientation relationship that means, this alpha and Fe₃C have a some kind of fixed orientation relationship crystallographic orientation and this is typically, referred to by the name of Kurdjumov-sachs relationship. And the Kurdjumov-sachs relationship is defined as the 1 0 0 plane in cementite is parallel to the 1 1 1 type of or 1 1 bar 1 plane in gamma.

The 0 1 0 of cementite is parallel to 1 1 0 of gamma, the 0 0 1 of cementite is parallel to 1 bar 1 bar 2 of gamma and we already noted cementite is an orthorhombic structure and we are noting the orientation relationship. Though at this stage is a little advanced topic for most beginners, but we have just noted that there is an orientation relationship between the alpha and Fe₃C. Now of course, next to the this Fe₃C plate on the other side again, you could have an nucleation of alpha and growth of alpha.

So, these 2 are alpha and this is now my Fe₃C and slowly I can have this process repeated again and again and i have what we might call a colony of pearlite grains. So, this is now my colony of pearlite. And so, I have my pearlitic colony further some of this

Fe₃C may actually branch and giving rise to richer microstructures due to this branching process.

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So, let us summarize the mechanism by which such a lamellar microstructure, the pearlitic lamellar microstructure which you see here in this micrograph. For instance you have this alternating lamella and between 1 2 lamella of alpha, there is a lamella of Fe₃C. How do we get such a lamellar microstructure is that, first we can assume that at the heterogeneous nucleation is a dominant process say for instance Fe₃C first forms at an interface between a gamma 1 and gamma 2 2 grains of gamma. After this nucleation we would note that typically there are, coherent and semi-coherent or coherent and semi-coherent and incoherent interfaces.


The incoherent interfaces are glissile or mobile and they grow and after certain growth of certain amount of Fe₃C you would notice that alpha nuclides in adjacent regions like here. And these alphas continue to grow and this process is repeated by adjacent nucleation of various alpha and Fe₃C lamella, that you get a pearlitic colony. and we also noted that the alpha and Fe₃C are not randomly oriented, but there is fixed orientation relationship. Typically, given by the Kurdjumov-sachs relationship which has being listed here below.

That means there is a crystallographic orientation between my alpha and Fe₃C. So, we have a brief idea of how the pearlitic transformation takes place by heterogeneous

nucleation at the gamma 1 gamma 2 boundaries. And especially, the role of the you might call the coherency of the interface in such a growth process.

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Bainite



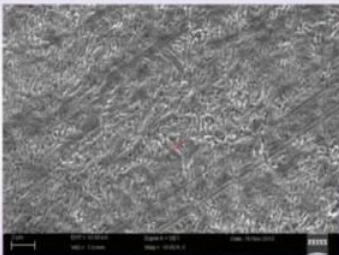

$\gamma \rightarrow \alpha + \text{Fe}_3\text{C}^{**}$

- Bainite formed at high temperature (~350°C) has a feathery appearance and is called 'Feathery Bainite'.
- Bainite formed at lower temperature (~275°C) has a needle-like appearance and is called 'acicular Bainite'.
- The process of formation of bainite involves nucleation and growth
- Acicular, accompanied by surface distortions
- ** Lower temperature → carbide could be ε carbide (hexagonal structure, 8.4% C)
- Bainite plates have irrational habit planes
- Ferrite in Bainite plates possess different orientation relationship relative to the parent Austenite than does the Ferrite in Pearlite

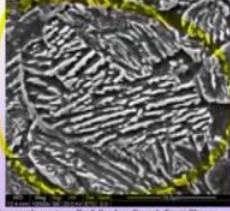
We had noted also another micro constituent, which is bainite and this bainite we have previously noted consists of alpha and Fe₃C. Now in case of bainite this way this alpha and Fe₃C is distributed is different and for instance, this is one picture of a bainite.

(Refer Slide Time: 30:47)

More images of Bainite

AFM image



0.8% C steel, the sample was quenched in a salt bath having 400°C temperature and then it was held for 2 hours.

And there are more pictures of bainite in the next slide here for instance, this shows you some rich microstructure of bainite here. And this is 0.8 person carbon sample which

was quenched in a salt bath at 400 degree Celsius and then held for 2 hours. So, we note that we have to hold isothermally to produce bainite and that means, continuous cooling cannot give us bainite.


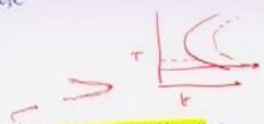
And this is another micrograph on the right hand side, where you see at a even higher magnification the bainitic structure. So, this is slightly different from the pearlitic structure. And even on the right hand side that you can see that there is a bainitic structure, where in you have these sheets of bainite which is shown in an A F M image.

So, this structure does not have this alternating lamella like in pearlite and typically these structures are finer because now the transformation is at a lower temperature where nucleation is the more dominant process. And therefore, you expect to obtain a fine structure of bainite.

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Bainite

$\gamma \rightarrow \alpha + \text{Fe}_3\text{C}^{**}$

- Bainite formed at high temperature (~350°C) has a feathery appearance and is called 'feathery Bainite'.
- Bainite formed at lower temperature (~275°C) has a needle-like appearance and is called 'acicular Bainite'.
- The process of formation of bainite involves nucleation and growth
- Acicular, accompanied by surface distortions
- ** Lower temperature → carbide could be ϵ carbide (hexagonal structure, 8.4% C)
- Bainite plates have irrational habit planes
- Ferrite in Bainite plates possess different orientation relationship relative to the parent Austenite than does the Ferrite in Pearlite

And this bainite has a higher hardness as compared to pearlite as we shall see soon. The bainite which is formed at higher temperatures say around 350 degrees Celsius isothermal hold has a feathery appearance and often called a feathery bainite. Bainite formed at lower temperature 275 degrees Celsius as a needle like appearance and what we meant by needle like or acicular appearance is that the structure actually consists of some needle like regimes.

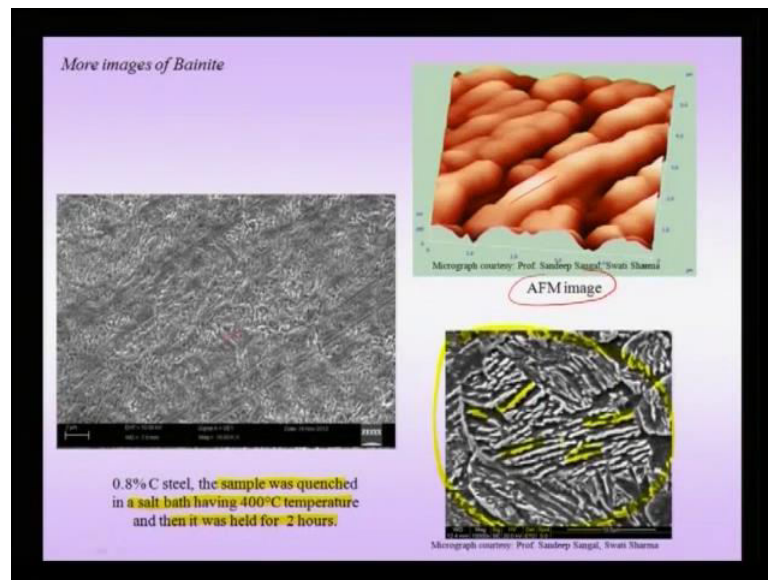
So, this my and the feathery appearance is meant that, it is actually has a very diffuse like feather like, outline instead of having sharp outline. So, that is how the feathery bainite looks and such a bainite with needle like shape is called a acicular bainite. So, this is my acicular bainite here.

The process of bainite formation again involves nucleation and growth, because this is not a shear deformation, shears involving process like martensitic transformation, but involve nucleation and growth. This acicular bainite formation involves surface distortions and we will note later that such kind of surface distortions are also observed in martensitic transformations. Now another additional complication comes because, at lower temperatures the carbide need not be the usual Fe_3C , but could be the orthorhombic Fe_3C , but could be epsilon carbide which is an hexagonal structure and which is more carbon in in it compared to the cementite.

So, we could suppose I do this transformation and I do not of course, I have to avoid the nose of the T T T diagram. So, I have my T T T diagram here for transformation of alpha to Fe_3C . Because, my usual axis would be temperature and time and suppose instead of doing at reasonably lower temperature, I go to even lower temperatures and do my transformation.

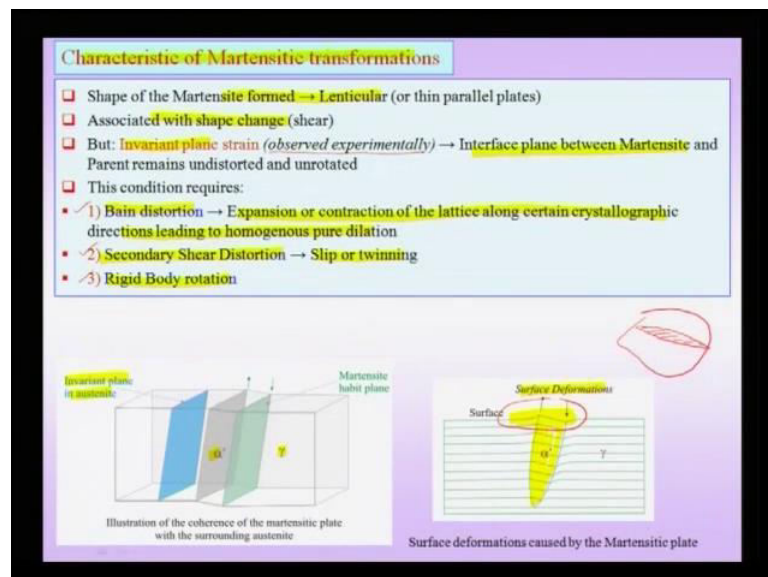
I may sometime obtain carbide known as the epsilon carbide, which has an hexagonal structure and which has even more carbon in it. So, we have considered here some aspects regarding bainitic transformation.

(Refer Slide Time: 33:52)



And we will come to the properties of such a bainite produced in one of the coming slides. So, once again let us have a closer look at the microstructure here, where we see that the bainite does not look lamellar as like the case and you can even see the outline of these some of these sheets are very very different as compared to the pearlite.

(Refer Slide Time: 34:10)



Now, let us try to understand some more details about the martensitic transformation. Martensitic transformation we shall of course, consider now for eutectoid steel and one of the important things, we said about the martensitic transformation was that it is

produced by a diffusion less process number one. Number two it we said it involve shear, number three we said it produces a very hard product in the case of the iron eutectoid steel.

And we have also noted that it is hard, but brittle phase and therefore, I would like to see that how this martensitic transformation takes place in steel, what are the issues involved crystallographically, and what are the issues involved with respect to the sample itself and the sample deformation. So, let us start with a few characteristics of the martensitic transformation. First of all that the shape of the martensite formed is lenticular or they consists of thin parallel plates and for instance this could be one of the martensitic plates which has been shown here as in labeled as alpha prime.

So, this is kind of a lens kind of a plate which forms. So, if you look at a grain of austenite within which such a martensite for instance would form. Then you may notice that suppose this is my grain of austenite, which is my martensite formed this is my martensite would form like a plate like this. Second thing of course, is that this process associated with shears or shape change and does not involve long range diffusion.

And this shape change can clearly be seen in the form of surface distortions as shown in the schematic here, that if this plate actually intersects the surface this shear leads to a distortion of the surface as clearly seen in this schematic drawn here. there is one characteristic, which is that there is one plane, which is called the strain is imposed in such a way the shear strain such that there is an invariant plane.

There is one plane which remains invariant during this entire transformation for instance suppose this is my phase level gamma in which I am forming my alpha prime, which is my martensitic phase then I would notice that, there is one plane which remains undistorted.

So, this is called the invariant plane and therefore, the strain has which is involved in this martensite formation has to be consistent with the fact that there is one invariant plane in the whole transformation. And this interface plane between martensite and parent place remains this invariant plane remains undistorted and un-rotated during the whole transformation. This whole process therefore, has to involve 3 steps. Step 1 and step 2, we will concentrate in the current set of slides.

That it involves what is called the crystallographic bain distortion or the bain deformation where in there is an expansion or contraction of the lattice along certain crystallographic directions leading to homogeneous dilation. So, the bain distortion itself leads to a certain dilatational process of course, the dilation dilatation depends on the x or y direction as we shall see in the coming slides. Now to keep an invariant plane certain secondary shear distortion is involved and this for instance has to be accommodated by either slip or twinning.

Further there is a need for a rigid body rotation, which we shall not talk about in the coming slides. So, let us summarize this slide before we see how this bain distortion takes place, how the secondary shear distortion takes place or why is the need for the secondary shear distortion to keep the invariant plane all these things. In this slide we are talking about a formation of a martensite, which is I called a lenticular morphology and this lenticular morphology gives rise to deformations.

Especially, if you if the plate intersects the surface as shown in the schematic below. Now this invariant plane strain, which is observed experimentally has to be understood in terms of 3 steps, which is the bain distortion this secondary shear distortion and a rigid body rotation.

(Refer Slide Time: 38:26)

Martensite

Change in Crystal Structure

$\gamma (FCC) \xrightarrow{\text{Quick}} \alpha' (BCT)$
 $0.8\%C \quad \quad \quad 0.8\%C$

- ❑ Martensitic transformation can be understood by first considering an alternate unit cell for the Austenite phase as shown in the figure below.
- ❑ If there is no carbon in the Austenite (as in the schematic below), then the Martensitic transformation can be understood as a -20% contraction along the c-axis and a $+12\%$ expansion of the a-axis \rightarrow accompanied by **no volume change** and the resultant structure has a BCC lattice (the usual BCC-Fe) \rightarrow c/a ratio of 1.0.

$\begin{matrix} \text{FCC Austenite alternate choice of Cell} \\ \downarrow \\ \text{A Body-Centered Tetragonal Cell} \end{matrix}$

 $\begin{matrix} \text{In Pure Fe after} \\ \text{the Martensitic transformation} \\ c = a \end{matrix}$

$\begin{matrix} \text{FCC} \rightarrow \text{BCC} \end{matrix}$

$\begin{matrix} -20\% \text{ contraction of } c\text{-axis} \\ -12\% \text{ expansion of } a\text{-axis} \end{matrix}$

So, the martensitic structure, we have the gamma F C C, which forms a body centered tetragonal structure the alpha prime structure. And the composition during this whole process and we produced martensitically by quenching.

Therefore I as we talked about, we taken water and quench of a sample from the austenite region, we can produce martensite and the composition does not change. That means, there is no long grain diffusion involved like in the case of formation of pearlite or bainite from the gamma. So, this martensite involves change in crystal structure that means, if you go from gamma F C C to alpha prime which is B C T. Now we have started here with 0.8 percent carbon steel first let us understand that suppose, we had pure iron, we do not have an 0.8 percent carbon steel what happens to this ah iron when we quench it from the gamma phase field or the gamma region.

So, the iron F C C has this kind of a lattice as shown here and for this we can choose an alternate unit cell as shown in the blue color. Please note that we are there is no phase transformation involved. So, for what we are talking about is the choice of an alternate unit cell as marked in blue color. Now this is an body centered tetragonal steel which can also as I will describe this F C C structure.

Only thing normally we do not choose is unit cell as a preferred unit cell, because of the fact that the cell has a lower symmetry as compared to lattice. Now if I cause phase transformation of this by quenching and I know at room temperature as iron has a B C C structure. So, the end product has to be a B C C structure, if i start with an F C C structure. And now I am assuming as you know there is no carbon involved in the process, this phase transformation involves contraction of the C axis that means, the C axis contracts, while the axes which is drawn here a new a axis, which is now my new a axis for the body centered tetragonal cell expands above 12 percent.

And so, therefore, there is an expand contraction along the C axis expansion along the A axis, such that the final product is 1 in which all my 3 lattice parameters along the a prime, which is here. For the new unit cell and this is of course, a originally a C axis, which is now also becomes a prime after the phase transformations. That means, that by this kind of a contraction by this kind of a deformation, I can understand how the B C C unit cell forms from the F C C structure and there is no volume change involved.

And the resulting structure B C C the C A ratio of the structure is 1. Because, now we have 2 lattice parameters a primes is constant and the C, which is now becomes the new a prime after 20 contraction is the same as the lattice parameter along the base cell directions. Therefore, if I take pure iron and quench it from the from high temperature, I have this F C C to B C C phase transformation. And the final product is as expected B C C C now the product B C C is not very hard because, now we are talking about pure iron and we will see later in the next slide.

(Refer Slide Time: 42:07)

Martensite

- In the presence of Carbon in the octahedral voids of CCP (FCC) γ -Fe (as in the schematic below) \rightarrow the contraction along the c-axis is impeded by the carbon atoms. (Note that only a fraction of the octahedral voids are filled with carbon as the percentage of C in Fe is small).
- However the a_1 and a_2 axis can expand freely. This leads to a product with c/a ratio (c'/a') $> 1 \rightarrow 1.1$.
- In this case there is an overall increase in volume of $\sim 1.3\%$ (depends on the carbon content) \rightarrow the Bain distortion*.

Bain distortion

Along the c-axis obstructs the contraction

Austenite to Martensite $\rightarrow \sim 1.3\%$ volume increase

Tetragonal Martensite

B C T
 $\frac{c}{a} \sim 1.1$

* Homogeneous dilation of the lattice (expansion/contraction along crystallographic axis) leading to the formation of a new lattice is called Bain distortion. This involves minimum atomic movements.

That suppose, I do not start a pure iron, but I start with an iron carbon alloy in the gamma phase field and quench it. For and now we will consider eutectoid composition, then i will obtain a hard product. So, we will see how this hard product this marten site is obtained. And in other words, if I have carbon, I do not land up with B C C, but I land up with the body centered tetragonal and we will try to understand how we this body centered tetragonal structure comes up on.

In the presence of carbon and we know that this carbon is present in the octahedral voids of the cubic closed pack crystal or the F C C crystal as commonly known as the contraction along the C axis is impeded by the carbon atoms. So, where are these carbon atoms present in the F C C. And of course now I have my original unit cell like here before, the F C C unit cell with these 3 as my reference axis.

Additionally I have my blue unit cell, which is now my body centered tetragonal unit cell and further in the same diagram, I have marked the positions where the carbon atoms could be potentially present. And you can notice that these carbon atoms are present some of them along the C direction like this one. These ones are present along the C direction, but there is no carbon atom present along, the new A prime direction.

So, there is no carbon atom along the A prime directions of the body centered tetragonal cell, but of course, since we are talking about a dilute solution of carbon in iron that implies not all the octahedral voids are occupied. Because, in an FCC structure or a cubic closed pack structure the number of octahedral voids are same as the number of the atoms in the unit cell. But therefore, only a very small fraction of the octahedral voids are occupied.

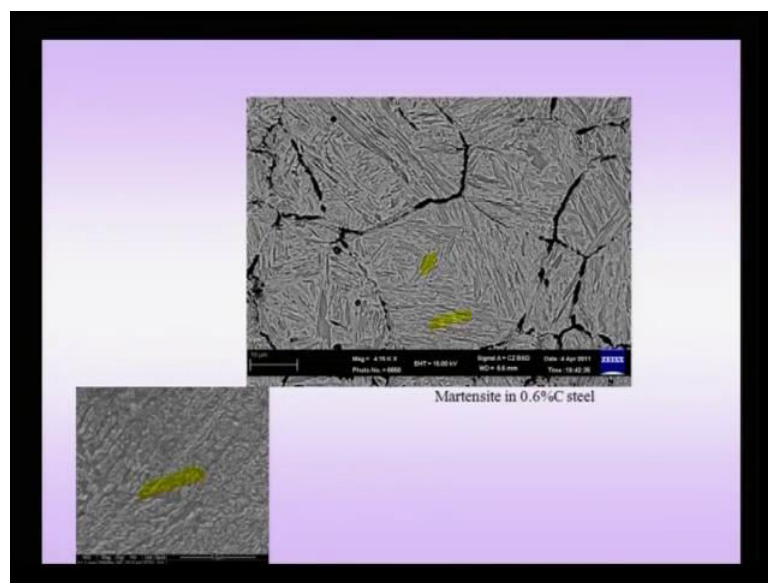
But what we have drawn here is are all the potential sites, where carbon atom can sit. And now when my bain distortion takes place or the distortion, which we saw previously at 20 percent contraction, along the C axis and 12 percent along the A axis. This kind of contraction tries to take place, when I quench from higher temperature you can notice that the 2 A axis as I am marking here.

This A axis are free to expand because, there are no carbon atoms in their path on the other hand the C axis is partially impeded by presence of carbon atoms the contraction. Which was 20 percent before and the product is such that, as I for instance we will see a carbon atom is sitting here this would obstruct my contraction along the C direction. And therefore, instead of obtaining a final product, which is BCC. I land up with a final product which is BCT structure. So, this now not my BCC, but a body centered tetragonal structure.

In which case the C axis is slightly larger than the A axis and this C to A ratio is of the order of 1 is to 1.1. So, this is slightly distorted body centered cubic structure, which is the body centered tetragonal structure, where in carbon atoms are sitting along the C direction like here, which are as again only a part of those potential sites are actually occupied by carbon. And this impediment gives rise to a body centered tetragonal structure. now the overall volume change involved is of the order of 4.3 percent and such a large volume change implies, that there is lot of strains involved in this martensitic transformation.

And these strains, if not relieve later on by heat treatments can actually cause, you know this material to be brittle and this can lead to cracking of the material. And needless to say this volume change depends on the amount of carbon present in the starting gastenite. So, we can now formally define, what is known as the bain distortion, homogenous dilation of the lattice, which is expansion or contraction along crystallographic axis. Leading to the formation of a new lattice is called the bain distortion and this involves minimum atomic moments. Because, we already noted that long range diffusion is not part of the martensitic transformation.

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So, we are now ready to summarize and of course, let us start this of course, see some typical martensitic microstructures. Again you can see that in martensite, again we have these kind of acicular structures, but this is a typical martensitic microstructure you would obtain. And needless to say such a product is actually brittle and would need further heat treatments to make it industrially important material. So, there are other microstructures of martensite which is not that clear, but this structure of martensite seems reasonably clear, when we see that there is all these martensitic sheets which are present.

(Refer Slide Time: 47:04)

Characteristic of Martensitic transformations

- ❑ Shape of the Martensite formed → Lenticular (or thin parallel plates)
- ❑ Associated with shape change (shear)
- ❑ But: Invariant plastic strain (observed experimentally) → Interface plane between Martensite and Parent remains undistorted and unrotated
- ❑ This condition requires:
 - 1) Bain distortion → Expansion or contraction of the lattice along certain crystallographic directions leading to homogenous pure dilation
 - 2) Secondary Shear Distortion → Slip or twinning
 - 3) Rigid Body rotation

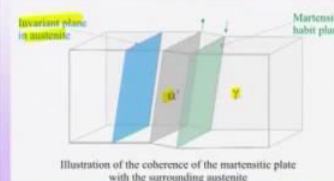
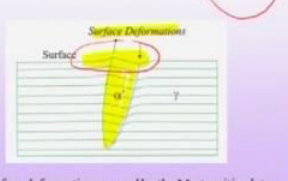


Illustration of the coherence of the martensitic plate with the surrounding austenite



Surface deformations caused by the Martensitic plate

So, let us summarize our details about martensitic transformation. So, martensitic transformation involves shear and typically, certain lenses of martensite form by and this shear process could lead to surface distortions. And to understand this martensitic transformation I need to understand bain distortion, that mean crystallographic distortions and secondary shear, which is accommodated by slipper twinning.

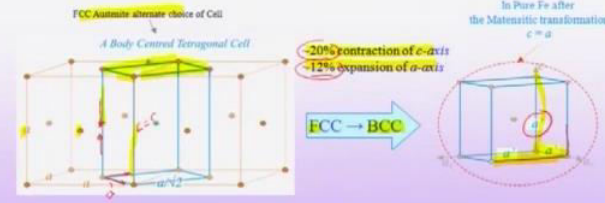
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Martensite

Change in Crystal Structure

γ (FCC) $\xrightarrow{\text{Quench}}$ α' (BCT)
0.8% C \rightarrow 0.8% C

- ❑ Martensitic transformation can be understood by first considering an alternate unit cell for the Austenite phase as shown in the figure below.
- ❑ If there is no carbon in the Austenite (as in the schematic below), then the Martensitic transformation can be understood as a -20% contraction along the c-axis and a +12% expansion of the a-axis → accompanied by no volume change and the resultant structure has a BCC lattice (the usual BCC-Fe) → c/a ratio of 1.0.



FCC Austenite alternate choice of Cell
A Body Centred Tetragonal Cell

In Phase Fe after the Martensitic transformation
c = a

-20% contraction of c-axis
+12% expansion of a-axis

FCC → BCC

And the first part which is the bain distortion we have understood.

So, for in which case we have noted that presence of carbon leads the stops the contraction along the C axis and therefore, leads to a body centered tetragonal structure in the end.

(Refer Slide Time: 47:43)

Martensite

Change in Crystal Structure

γ (FCC) $\xrightarrow{\text{Quench}}$ α' (BCT)
0.8% C \rightarrow 0.8% C

- Martensitic transformation can be understood by first considering an alternate unit cell for the Austenite phase as shown in the figure below.
- If there is no carbon in the Austenite (as in the schematic below), then the Martensitic transformation can be understood as a $\sim 20\%$ contraction along the c-axis and a $\sim 12\%$ expansion of the a-axis \rightarrow accompanied by **no volume change** and the resultant structure has a **BCC** lattice (the usual BCC-Fe) \rightarrow c/a ratio of 1.0.

And not a body centered cubic structure and this process overall involves lot of strains about 4.3 percent volume change. And this strain is accommodated with in the microstructure and therefore, such a material unless this residual strain is relieved somehow can lead to lot of cracking in the material.

(Refer Slide Time: 48:06)

Irrational Habit Plane
(Should remain undistorted and unrotated)

Dilation due to phase transformation
(Rotated due to the transformation)

Shear
(Combined Dilation and Shear leaves Habit Plane Invariant)

But shear will distort the lattice!

Slip Twinning

Average shape remains undistorted

Now, let us try to understand why do we need this shear to accommodate this invariant plane strain condition. So, let us assume that there is an plane here and this of course, these are schematics to understand this. There is a plane for instance the one draw in red, a crystallographic plane and typically, this is an irrational plane and this is also called the irrational habit plane. And this irrational habit plane has to remain undistorted during this whole process of martensitic transformation. Now step one of course, is what we saw is some kind of a dilation or contraction and let us consider dilation ah of this lattice.

So, during this dilation you notice that this plane, which is originally present here has gone to the new position which is now marked in red. So, this is my new position of the plane that means, that now my plane which was expected to remain exactly in the original place undistorted has got distorted. In fact, it has got stretched because the original length was A , A' and now the new position is $A B'$ and the $A B'$ prime is longer than $A A'$ prime.

Now to accommodate the fact that, they you do experimentally observe an invariant plane strain condition, we have we can actually understand it by imposing, what we call secondary shear and the secondary shear can cause shear of this structure. So, but bring the plane originally plane back to the $A A'$ prime condition. Of course, this leaves the plane $A A'$ prime undistorted. Therefore, i get my invariant plane strain condition, but the problem is here that suppose, I shear my crystal as such then the crystallographic of the in other words I will land up with a lower symmetry crystal. But, this is not observed and therefore, what we see how is this shear accommodated is by 2 processes typically.

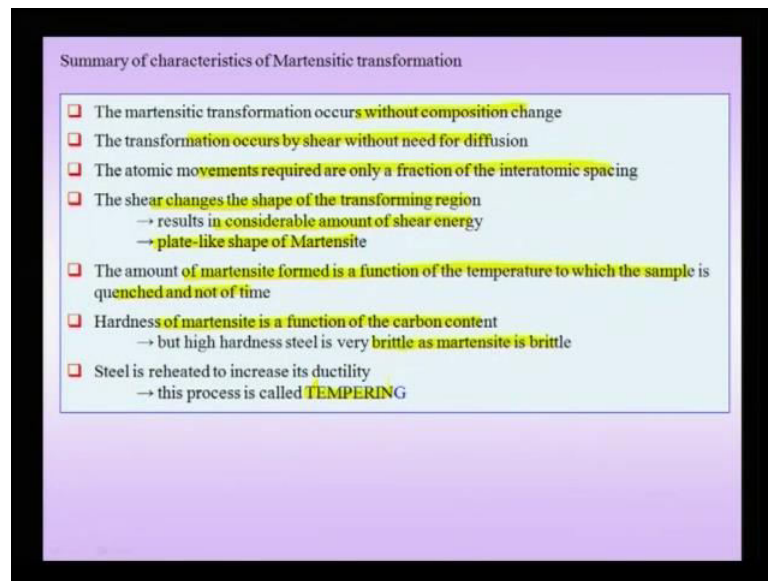
One is by slip or twinning. So, for instance in the left hand side there is schematic which says that, even though I have a shear on an average I can have an undistorted crystal structure. That means, the unit cell of the crystal does not get distorted, but I can have and this is therefore, 2 mechanisms by which this secondary shear is accommodated 1 is slip, another is twinning in slip.

Of course, I can see that the unit cell remains the same and now I have a shear being accommodated that means, the average shape remains undistorted. So, I can have with that or in the right hand side of course, you can see that these plane crystallographic planes are twinning and this twin can actually accommodated my shear. Please note that of course, this is not my new unit cell, what we have drawn here are these kind of planes,

which are being reflected and therefore, this is shown the reflection of these planes, that means, now this is my twin planes.

So, these are my twin planes. So, this twinning leads to twinning can be used to actually accommodate my secondary shear. But, we have to note that, we do need secondary shear to understand the invariant plane strain and the shear can be accommodated either by slip or by twinning.

(Refer Slide Time: 51:30)



So, let us summarize the characteristics of the martensitic transformation. The martensitic transformation obviously, occurs without a change in composition that means, if I start with the eutectoid steel.

I will land up with eutectoid steel and the process occurs by shear deformation with no need for long range diffusion. Atomic moments required only are a fraction of the inter atomic spacing as we have seen that, this bain distortion does not involve or the secondary shear does not involve large scale atomic moments. The shear changes the shape of the transforming region results in considerable amount of shear energy and also is responsible for the plate like shape of martensite the lenticular shape.

The amount of martensite formed is a function of the temperature to which the sample is quenched and not a function of the time to which you hold a sample. The hardness of

martensite is further a function of the carbon content, but with in increasing carbon content, though the hardness increases.

But also the sample becomes more and more brittle and we will have to undertake treatments like tempering to actually get some amount of ductility back in other words, I can do a quench treatment, which gives martensite. And so, this quenching has to be followed by tempering treatment. So, that I have a combination of ductility and strength in other words the toughness of my sample can be enhanced.