Mechanical Behavior of Materials
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Module No # 08
Lecture No # 43
Creep – I

Hello I am Professor S. Sankaran in the department of metallurgical and materials engineering. Hello everyone welcome to this lecture in today's lecture we will turn our attention to high temperature deformation called creep. And the word creep defines you know the time dependent deformation. We have given some introduction to this time dependency of you know elastic deformation we have seen it in anelasticity.

In general we have looked at anelasticity in detail and we also have given some examples and how anelasticity is going to play a role in the deformation of materials. So you have to recall that chapter and we are going to connect that anelasticity behaviour but only difference is here it is plastic deformation. Earlier we looked at primarily in an elastic deformation that is time dependent elastic deformation and now it does plastic deformation.

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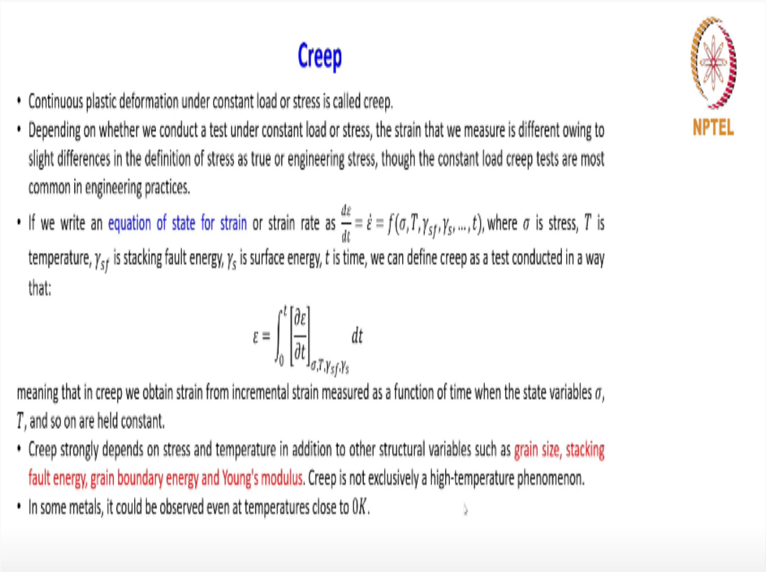

Creep

- Continuous plastic deformation under constant load or stress is called creep.
- Depending on whether we conduct a test under constant load or stress, the strain that we measure is different owing to slight differences in the definition of stress as true or engineering stress, though the constant load creep tests are most common in engineering practices.
- If we write an equation of state for strain or strain rate as $\frac{d\varepsilon}{dt} = \dot{\varepsilon} = f(\sigma, T, \gamma_{sf}, \gamma_s, \ldots, t)$, where σ is stress, T is temperature, γ_{sf} is stacking fault energy, γ_s is surface energy, t is time, we can define creep as a test conducted in a way that:

$$\varepsilon = \int_0^t \left[\frac{\partial \varepsilon}{\partial t}\right]_{\sigma, T, \gamma_{sf}, \gamma_s} dt$$

meaning that in creep we obtain strain from incremental strain measured as a function of time when the state variables σ, T, and so on are held constant.

- Creep strongly depends on stress and temperature in addition to other structural variables such as grain size, stacking fault energy, grain boundary energy and Young's modulus. Creep is not exclusively a high-temperature phenomenon.
- In some metals, it could be observed even at temperatures close to $0K$.

So there are several ways by which you can one can define a creep, but simply you can just tell in the layman language this is a continuous plastic deformation under constant load or stress is called creep. Of course it is a high temperature phenomenon but in a very simplified definition can be like this. Depending on whether we conduct the test under the constant load or stress the strain that we measured is different going to slight differences in the definition of stress as true or engineering stress. This we know, why we call it as true stress and engineering stress. We have already seen this though the constant load tests are most common in engineering practices. So we are going to talk about mostly on the constant load creep test. Of course we can do constant stress strain test that requires some special setup in the machine but most of the testing machines conventionally used in the lab is constant load creep test or creep testing machines which are being used. If you write an equation of state for strain or strain rate as d ε/ dt is equal to $\dot{\varepsilon}$

Normally it is represented as a creep rate which is a function of stress, temperature, γ and sf (stacking fault energy) andγ_s is the surface energy etc., including time where σ a is stressT temperature stacking called energy. Yes, I just said it we can define the creep as a test conducted in a way that we can measure the strain over period of time that is 0 to t.

The change in strain with respect to time that is d $\partial\varepsilon/ \partial t$, at constant stress σ_t γ, sf, γ_s. So we can write creep strain in this integral form meaning that in a creep we obtain a strain from incremental strain measured as a function of time very important. We are looking at $\varepsilon$by∂t that is clearly indicates it is an incremental strain. That is why we use this ∂ ε by ∂ t measured as a function of time when the state variables such as sigma t and so on are held constant so that is why we have put all these state variables. So this is one nice way of representing the creep strain how it can be defined or how it can be visualized. Creep strongly depends on the stress and temperature in addition to other structural variables such as grain size, stacking fault energy, grain boundary energy and Young's modulus. Creep is not exclusively a high temperature phenomenon. So this particular sentence says that you know the creep is strongly depends upon the stress and temperature that is how primary variable that it depends on.

Of course we have other variables and when it comes to define high temperature, it is something relative always right. So high temperature for, one x material may not be a higher temperature for other. So that is how this sentence is brought in, like it is not necessarily in a high temperature phenomena because you can depending upon the melting point of any material the temperature can be defined as a low temperature of high temperature right, so that is why it is said like that. In some metal it could be observed even at temperatures close to 0 Kelvin so this is something somebody has reported that kind of behavior so it is generally said like that. We will see how we will define this high temperature load temperature phenomena I mean the discrepancy how do we normalize creep. It is very important and interesting as well.

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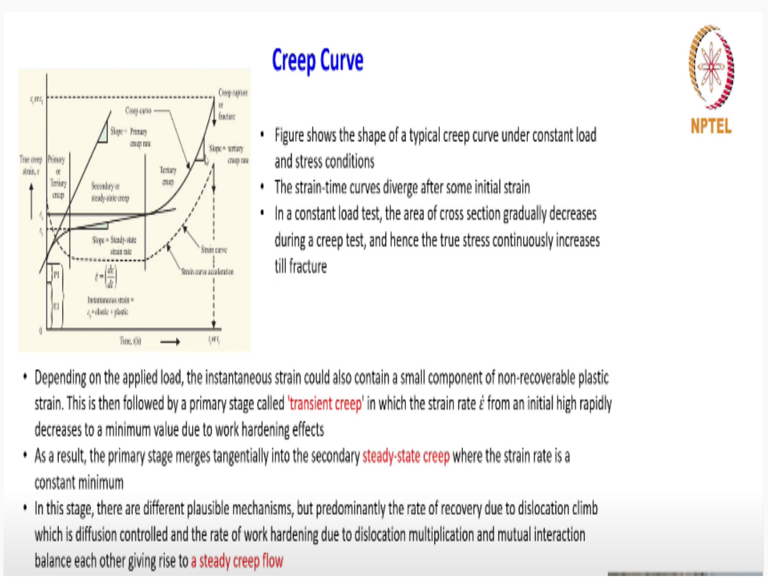

Creep Curve

- Figure shows the shape of a typical creep curve under constant load and stress conditions
- The strain-time curves diverge after some initial strain
- In a constant load test, the area of cross section gradually decreases during a creep test, and hence the true stress continuously increases till fracture

- Depending on the applied load, the instantaneous strain could also contain a small component of non-recoverable plastic strain. This is then followed by a primary stage called 'transient creep' in which the strain rate $\dot{\varepsilon}$ from an initial high rapidly decreases to a minimum value due to work hardening effects
- As a result, the primary stage merges tangentially into the secondary steady-state creep where the strain rate is a constant minimum
- In this stage, there are different plausible mechanisms, but predominantly the rate of recovery due to dislocation climb which is diffusion controlled and the rate of work hardening due to dislocation multiplication and mutual interaction balance each other giving rise to a steady creep flow

So we will now look at something called a creep curve and which is schematized in this figure. And it is quite you know cluttered here but then we will slowly look at it, but I brought this diagram because it is very, you know illustrative and very useful if you get everything in one shot so we will go through one by one. So what is being plotted it is a true creep strain ε versus time (t) in hours. So, the creep curve goes like this and then so what is shown here is an instantaneous strain that is what written here. You can have an elastic component as well as a plastic component. So time dependent elastic strain or recoverable strain time dependent plastic strain are non-recoverable or unrecoverable string. So this is as a two interesting components and then the creep strain goes like this and then it reaches a steady state and then it again accelerates and then fracture it called creep fracture or fracture it goes like that. And basically this creep curve has been divided into 3 regions that is the primary region or secondary or steady state region and tertiary.

So there are three possible regions of this curve have been described here. And what is the other curve, is the dotted line which is an overlapping plot on this creep curve. So this dash line is a creep rate that is $\dot{\varepsilon}$ which is equal to (dε/dt) that is superimposed on this creeper. So do not get confused this is a creep rate versus time and this is a strain versus time. There are two plots superimposed on this because it is I just particularly showed this. Because we will be able to describe so many things in one place and which is very it is also very useful to correlate the parameters.

So figure shows the shape of typical creep curve under the constant load and stress conditions okay. So, typically as I mentioned it is done in a constant load. So typically the setup of the creep testing is also you should know it is nothing it will be a similar to high temperature testing setup only except the strain will be very very low. And you know the load which we can vary will be slightly different rest all the same. The strain time curves diverge after some initial strain that is what we have just said. In a constant load test, the area of the cross section gradually decreases during the creep test and hence the true stress continuously increases still fracture. Depending on the applied load the instantaneous strain could also contain a small component of non-recoverable plastic strain. So this is what I just said in the beginning. So you have time dependent non recoverable plastic strain, this is then followed by a primary stage called a transient field so this region is called a transient creep, in which the strain rate ε from an initial high rapidly decreases to a minimum value due to what carnival. So you look now just look at the dotted line the initially it is very high and then it just drops and reaches the plateau here steady state. And we are talking about it is due to what is hardening effect? So that means you see the initially after the instantaneous strain this curve it goes like this that means it work hardens. So you can just match this two curves and then see how the plateau regions are matched here so that is the reason I just brought this figure to compare the strain rate decreases the strength takes place because the strength increases because of the strain hardening effect. As a result the primary stage merges tangentially into the secondary steady state creep so that this plot is called steady state. So we will discuss in elaborate manner why it is called steady state?

So what you have to understand is some material exhibiting this kind of behaviour that means that could be two equally I would say powerful forces I think are equally possible reaction taking place, the one which causing the work hardening and one which causing the work softening. So then only this kind of plateau region, steady state comes we will see the details one by one. In this stage there are different possible mechanisms but predominantly the rate of recovery due to dislocation climb. So we are talking about high temperature deformation so obviously the dislocation climb which is a diffusion controlled process this also we have discussed already right the dislocation climb is a diffusion controlled process and the rate of work hardening due to dislocation multiplication. Of course we know what is workhardnening? And so on so during which the dislocation multiplication takes place and mutual interaction balance each other giving rise to a steady state on a steady creep flow so this is one very quick way of explaining this.

How the steady state you know reaches in this during creep deformation. We will look at the details slowly. This is the most important state or stage in industrial applications and it is in this stage that design criteria or creep resistance are evolvedthe very important point you have to remember so in a creep test during this period that is during the steady state period only the creep rate is measured that is also called the minimum creep rate (M C R), we will see it soon.

And that is a design parameter so you have to remember M C R is the design parameter like yield strength is also a design parameter right so here M C R is the design parameter.

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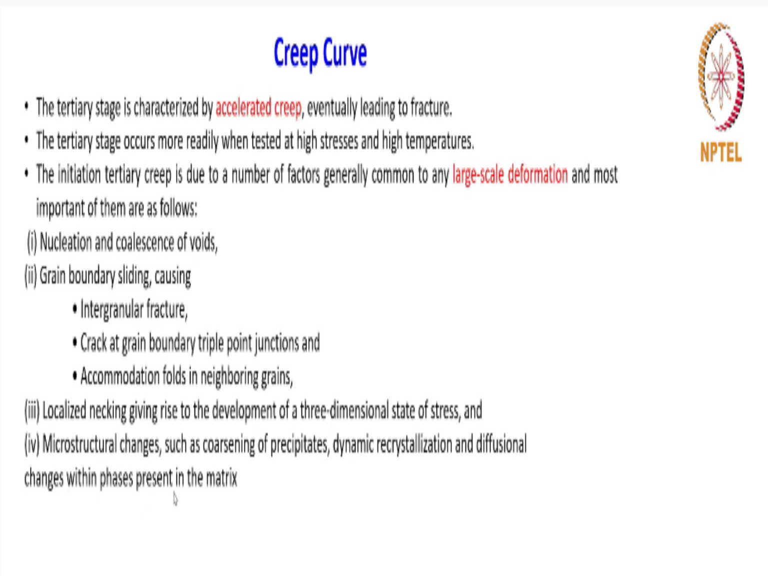

Creep Curve

- The tertiary stage is characterized by accelerated creep, eventually leading to fracture.
- The tertiary stage occurs more readily when tested at high stresses and high temperatures.
- The initiation tertiary creep is due to a number of factors generally common to any large-scale deformation and most important of them are as follows:

(i) Nucleation and coalescence of voids,
(ii) Grain boundary sliding, causing
  - Intergranular fracture,
  - Crack at grain boundary triple point junctions and
  - Accommodation folds in neighboring grains,
(iii) Localized necking giving rise to the development of a three-dimensional state of stress, and
(iv) Microstructural changes, such as coarsening of precipitates, dynamic recrystallization and diffusional changes within phases present in the matrix

We will continue to describe this tertiary stage is characterized by the accelerated creep. Eventually leading to fracture what is that we are seeing now? We are saying this is a tertiary now after steady state we are quickly seeing that what is this? So this is a tertiary you can see that the rate is very high slope is very high and it goes all the way up to the fracture. The tertiary stage occurs more readily when tested at high stresses and high temperatures.

So all that you have to remember always, is whenever you talk about tertiary stage it is always high stresses and high temperature combination. The initiation of tertiary creep is due to a number of factors generally common to any large scale deformation please, understand this. So this is not a local deformation it is a large scale deformation and most important of them are nucleation and coalescence of voids grain boundary sliding.

Which is causing, inter granular fracture or crack at grain boundary triple point junctions and accommodation of folds in neighbouring grains. So these are all some of the saline features which will clearly manifest themselves for the tertiary creep. And localized necking giving rise to a development of three dimensional state of stress so making we have discussed elaborately by necking accompanies or necking region experiences free dimensional state of stress this we have already studied. Microstructural changes such as; coarsening of precipitate dynamic recrystallization and diffusional changes within the phase present in the matrix. So it is not just the above features but the microstructural changes also will contribute to this I mean we will accompany this tertiary creep such as coarsening of crystalline. Because of very high temperatures we are talking about or even a strain induced precipitation also will take place dynamic recrystallization because we know what is dynamic recrystallization and diffusional changes because it is very high temperature within the phase all will contribute to this tertiary creep.

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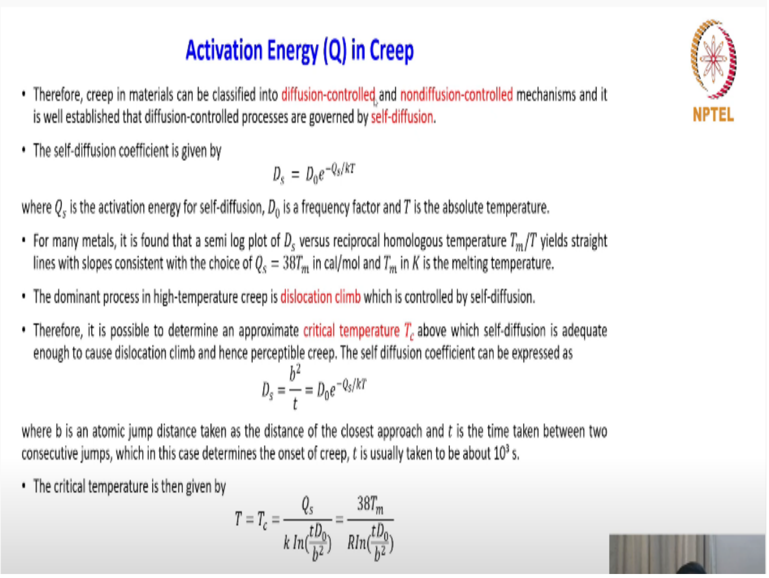

Activation Energy (Q) in Creep

NPTEL

- Therefore, creep in materials can be classified into diffusion-controlled and nondiffusion-controlled mechanisms and it is well established that diffusion-controlled processes are governed by self-diffusion.
- The self-diffusion coefficient is given by

$$D_s = D_0 e^{-Q_s/kT}$$

where Q_s is the activation energy for self-diffusion, D_0 is a frequency factor and T is the absolute temperature.

- For many metals, it is found that a semi log plot of D_s versus reciprocal homologous temperature T_m/T yields straight lines with slopes consistent with the choice of $Q_s = 38T_m$ in cal/mol and T_m in K is the melting temperature.
- The dominant process in high-temperature creep is dislocation climb which is controlled by self-diffusion.
- Therefore, it is possible to determine an approximate critical temperature T_c above which self-diffusion is adequate enough to cause dislocation climb and hence perceptible creep. The self diffusion coefficient can be expressed as

$$D_s = \frac{b^2}{t} = D_0 e^{-Q_s/kT}$$

where b is an atomic jump distance taken as the distance of the closest approach and t is the time taken between two consecutive jumps, which in this case determines the onset of creep, t is usually taken to be about 10^3 s.

- The critical temperature is then given by

$$T = T_c = \frac{Q_s}{k\,In(\frac{tD_0}{b^2})} = \frac{38T_m}{R In(\frac{tD_0}{b^2})}$$

So now we will see something called activation energy in creep, what is this? So we have just looked at all you know the consequences of this tertiary grade. So therefore creep in materials can be classified into diffusion controlled and non-diffusion controlled mechanisms, very important point. So now we are now trying to classify the creep mechanisms because we are saying too many things are happening in the material as the creep deformation proceeds.

So the primary classification come under these two categories one is diffusion control and the non-diffusion controlled mechanisms. And it is well established that diffusion controlled process are governed by self-diffusion this is again a very important point. Diffusion controlled process are governed by self-diffusion. How do we say that and what basis we are saying that? We will just look at it some experimental evidence. Before we get into that let us see the self-diffusion coefficient how it is defined it is given by $D_s = D_0 e^{-(Q_s / KT)}$. Where Q s is the activation for self-diffusion and D_0 is a frequency factor and T is the absolute temperature. For many metals it is found that a semi log plot of D_s versus reciprocal homologous temperature T_m/T yields straight lines with slopes consistent with the choice of $Q_s = 38 T_m$ in calories/ mol and T_m in kelvin is the melting temperature. So for many metals the Q_s that is the activation energy for the self-diffusion is given by $Q_s = 38 T_m$. How do we get this? We will see it in a minute, the dominant process in high temperature creep is dislocation climb which is controlled by self-diffusion. Therefore it is possible to determine an appropriate critical temperature T_c where above which self-diffusion is adequate enough to cause dislocation claim and hence perceptible creep. The self-diffusion coefficient can be expressed as $D_s = b^2/t$ which is equal to $D_0 e^{-(Q_s/KT)}$ where b is an atomic jump distance taken as the distance of the closest approach and D is the time taken between two consecutive jumps which in this case determines the onset of creep, t is usually taken to be about 10 to the power 3 second. So while we are now trying to look at the expression for the diffusion coefficient for self-diffusion in pure metals. Basically we just try to understand how this term arises then we can relate to other parameters. What is this critical temperature? The critical temperature is then given by

$$T = T_c = \frac{Q_s}{K \ln\left(\frac{t D_0}{b^2}\right)} = \frac{38\, T_m}{R \ln\left(\frac{t D_0}{b^2}\right)}$$

What is critical temperature here? Critical temperature above which self-diffusion is adequate enough.

So that means below this critical temperature we will not assume that it is diffusion controlled creep like we have discussed in the classification then we will be discussing that as non-diffusion controlled mechanism.

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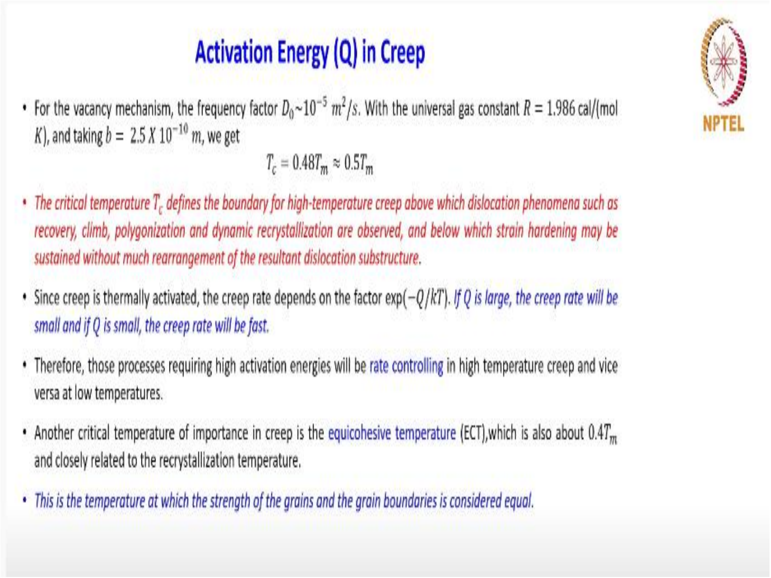

Activation Energy (Q) in Creep

- For the vacancy mechanism, the frequency factor $D_0 \sim 10^{-5}\ m^2/s$. With the universal gas constant $R = 1.986$ cal/(mol K), and taking $b = 2.5 X 10^{-10}\ m$, we get

$$T_c = 0.48T_m \approx 0.5T_m$$

- *The critical temperature T_c defines the boundary for high-temperature creep above which dislocation phenomena such as recovery, climb, polygonization and dynamic recrystallization are observed, and below which strain hardening may be sustained without much rearrangement of the resultant dislocation substructure.*
- Since creep is thermally activated, the creep rate depends on the factor $\exp(-Q/kT)$. *If Q is large, the creep rate will be small and if Q is small, the creep rate will be fast.*
- Therefore, those processes requiring high activation energies will be rate controlling in high temperature creep and vice versa at low temperatures.
- Another critical temperature of importance in creep is the equicohesive temperature (ECT),which is also about $0.4T_m$ and closely related to the recrystallization temperature.
- *This is the temperature at which the strength of the grains and the grain boundaries is considered equal.*

For the vacancy mechanism the frequency factor D_0 is approximately equal to 10^{-5} meter^2/ s. And with the universal constant gas constant R = 1.986 calorie per mol per kelvin and taking b= 2.5×10^{-10}m, we get T_c = 0.48 tm approximately 0.5 T_m. So the critical temperature is worked out to be 0.5 T_m. There is another temperature which is also similar range called recrystallization temperatures that is also very important temperature. So the critical temperature which is also sometimes I mean closely related to that recrystallization temperature right that is also in will be of similar order. The critical temperature T_c defines the boundary for high temperature creep above which dislocation phenomenon phenomena such as recovery claim polygonization and dynamic recrystallization are observed and below which strain hardening may be sustained without much rearrangement of resultant dislocation substance. So this T_c decides whether the creep deformation can be dominated by a diffusion controlled mechanism or non-diffusion control mechanism. Since creep is thermally activated the creep rate depends on the factor $e^{-Q/kt}$ so this is very important point to remember. So now by looking at this expression we can say if Q is large what will happen? If the Q is large the creep rate will be small and if Q is small the creep rate will be faster. So this is very important, if you know the activation energy so you will be able to judge the kind of creep rate. Therefore those processes requiring high activation energy will be rate controlling in high temperature creep and vice versa at low temperatures. So ultimately what is the process which is going to control the rate of the deformation. Another critical temperature of importance in creep is the equicohesive temperature (ECT), equicohesive temperature which is also about 0.4 T_m.

So we are now bringing lot of critical temperatures we are defining T_c above which the diffusion control mechanism to operate we were talking about recrystallization temperature which is also on the order of same at 0.5 or 0.4 T_m. Now we are talking about epuicohesive temperature which is also in the range of 0.4 T_m and closely related to recrystallization temperature again.

So what is the importance of this ECT? This is the temperature at which the strength of the grains and the grain boundaries is considered equal very important point. So, at this temperature both grain boundary and grains have a similar strength. So normally how do we understand the grain boundaries, brain boundaries are high energy regions right. But in this temperature both of them will have equal strength so what is the use? How do we recognize the influence of this?

Suppose if the T the operating temperature is greater than ECT then what will happen? Then what happens? Then the grain boundary will become weaker, then the fracture will happen in the, inter crystalline manner, the fracture will be intra crystalline image. In the other ways it is a trans crystalline image that means the T is less than ECT then the fraction will be trans crystalline image or if it is the first case is inter crystalline the second case is trans crystalline image.

So it gives some idea in the very beginning itself if you know what is the temperature and so on. That is why we just look at all these parameters.