Mechanical Behavior of Materials
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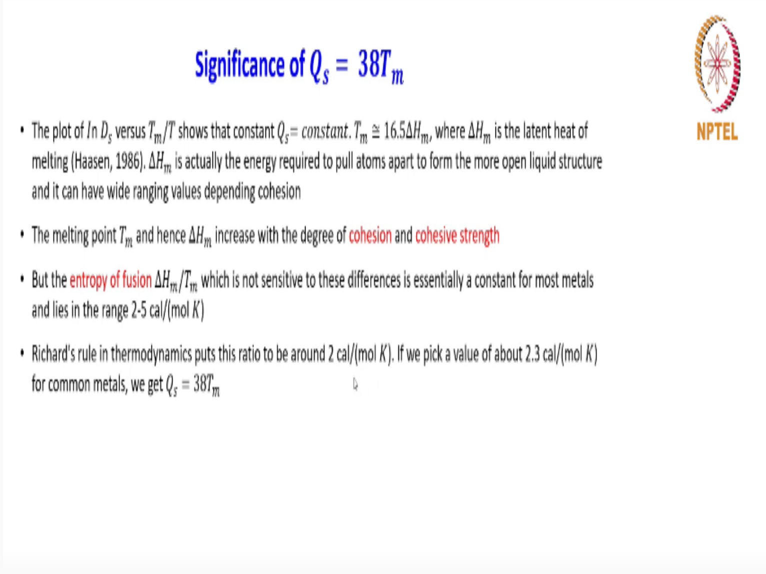
Module No # 09
Lecture No # 44
Creep – II

Hello I am Professor S.Sankaran in the department of metallurgical and materials engineering. **(Refer Slide Time: 00:17)**



Significance of $Q_s = 38T_m$

- The plot of $In\ D_s$ versus T_m/T shows that constant $Q_s = constant.\ T_m \cong 16.5\Delta H_m$, where ΔH_m is the latent heat of melting (Haasen, 1986). ΔH_m is actually the energy required to pull atoms apart to form the more open liquid structure and it can have wide ranging values depending cohesion
- The melting point T_m and hence ΔH_m increase with the degree of cohesion and cohesive strength
- But the entropy of fusion $\Delta H_m/T_m$ which is not sensitive to these differences is essentially a constant for most metals and lies in the range 2-5 cal/(mol K)
- Richard's rule in thermodynamics puts this ratio to be around 2 cal/(mol K). If we pick a value of about 2.3 cal/(mol K) for common metals, we get $Q_s = 38T_m$

The significance of the activation energy (Q_s) which; is normally derived as 38 T_m. How do we understand this? The plot of Lon Ds versus T $_m$ b T that is homologous temperature shows that constant Q $_s$ which is again this plot shows these Q $_s$ is constant so there is some typo here. Where T $_m$ is approximately is equal to 16.5 Δ H m where Δ H m is the latent heat of melting according to Haasen and Δ H m is actually the energy required to pull atoms upon to form the more open liquid structure and it can have wide ranging values depending on cohesion. The melting point tm and hence Δ h m; increase with the degree of cohesion and cohesive strength. But the entropy of fusion which is Δ H/ T , which is not sensitive to these differences is essentially a constant for most metals and lies in the range of 2 to 5 calories per moles per kelvin. So we are now trying to justify how we relate this activation energy to this value and it has got some thermodynamic basis. So Richard's rule in thermodynamics puts this ratio to be around 2 calories per kelvin per mole and if we pick a value of about 2.3 calories per mole per kelvin for common metals we get $Q_s = 38\ T_m$. So this is the basis of getting this Q_s based on this thermodynamic consideration just to give an idea, how; we get the activation energy for self-diffusion in a few metals.

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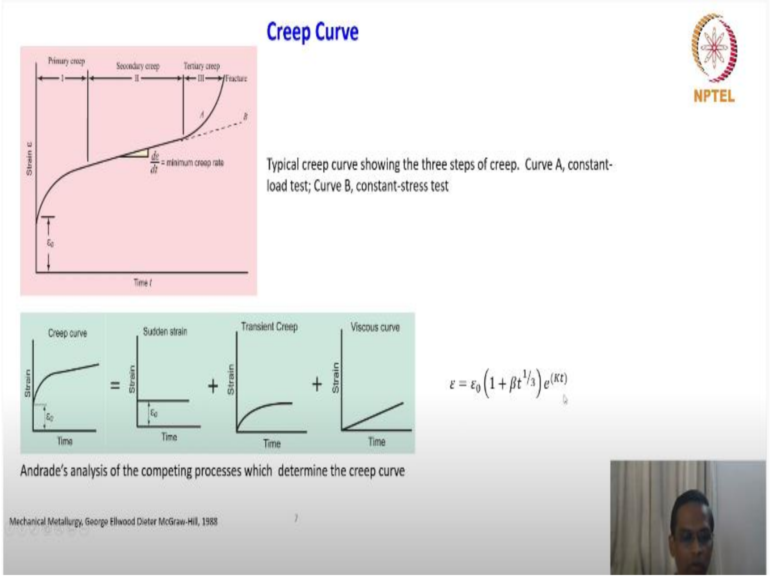

Creep Curve

Typical creep curve showing the three steps of creep. Curve A, constant-load test; Curve B, constant-stress test

$$\varepsilon = \varepsilon_0\left(1 + \beta t^{1/3}\right) e^{(Kt)}$$

Andrade's analysis of the competing processes which determine the creep curve

Mechanical Metallurgy, George Ellwood Dieter McGraw-Hill, 1988

So now we look at the creep curve. we have already seen that but then there are other perspective several authors have described the creep curve in a different way we will look at once again what is that? So this is a creep curve showing three steps of creep that we have already seen. Curve A is a constant load and curve B is a constant stress test. So Andrade's analysis of competing processes which determine the creep curve. So Andrade's has analyzed the creep curve under the constant stress which is this and he decomposed into three curves one is a sudden strain that is instantaneous strains plus the transient region. That is where the creep rate suddenly decreases and then reaches the steady state plus a constant viscous constant rate viscous creep. And then he just gave an empirical equation for the creep strain which is equal to

ε is equal to $\varepsilon_0\ (1+ \beta t^{1/3})\ e^{(Kt)}$

Where ε_0 is instantaneous strain and beta and k are the constants. So this equation if you put k which is the increment per unit length for a constant strain I mean constant rate, it will I mean if it becomes 0 then the transient creep will be exhibited by β so that is one way of looking at.

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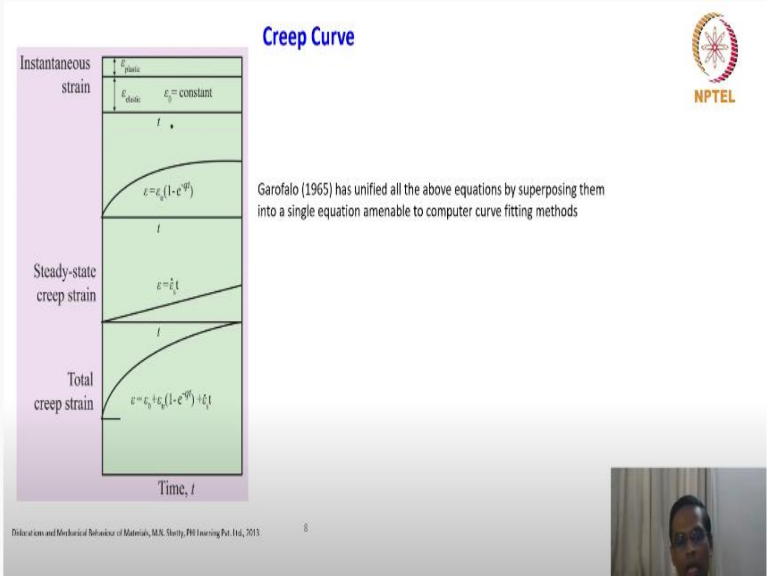

Creep Curve

Garofalo (1965) has unified all the above equations by superposing them into a single equation amenable to computer curve fitting methods

Dislocations and Mechanical Behaviour of Materials, M.N. Shetty, PHI Learning Pvt. Ltd., 2013

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Some other people have improved this equation and then what they have shown is a similar decomposition of the creep curve into instantaneous strain and transient creep and viscous creep and then this is a total creep strain which is given by this equation. So this particular equation is called you know exponential creep and this term ε_{tr}(means ε true times) (1- e^{-qt})is called a transient creep term and where q is the ratio between the strain rates to the creep strain? And this is a steady state creep strain and then if you put together then you see this instantaneous strain plus a transient creep strain plus steady state components. So this particular equation is proposed by Garofalo has unified all the above equations by superposing them into a single equation available to computer curve fitting methods. So by putting this kind of an equation people are able to compare for how many materials follow this kind of an empirical equation during creep.

So creep as I just mentioned is a strong function of stress temperature strain rate and these are primary. But then you have whole other structural features which are going to influence this so each particular combination of stress strain rate temperature will drive each material class into different different segments. So that is why all this you know the individual steps which we are which are shown in here they were all actually shown by some of the materials at some particular stress temperature combinations.

It is nothing is general here so people try to get a unified approach whether we can create one empirical equation. Which; is suitable for most of the material that was the attempt so that is how this all kind of equations is developed. But then only not that every material is going to follow but then these kind of empirical relations gives us an idea what are the critical parameters which governs this creep deformation and that is one advantage when you have this quantitative data though it is semi empirical or empirical image.

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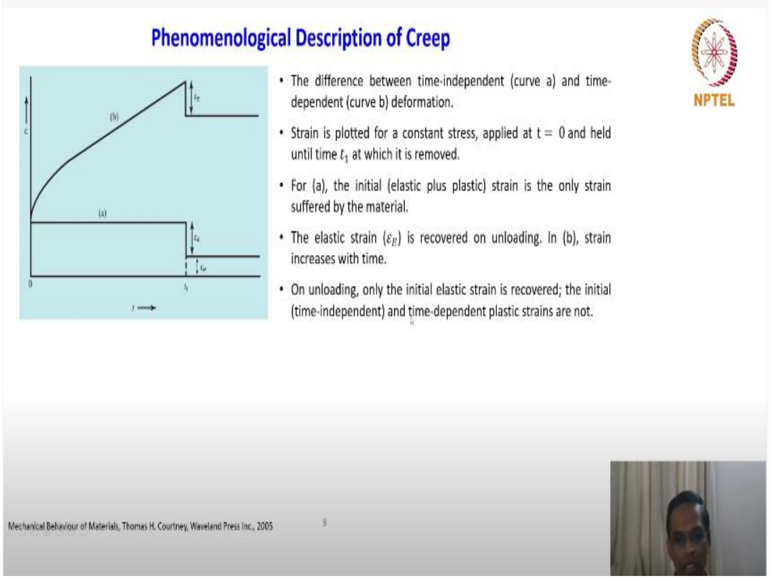

Phenomenological Description of Creep

- The difference between time-independent (curve a) and time-dependent (curve b) deformation.
- Strain is plotted for a constant stress, applied at t = 0 and held until time t_1 at which it is removed.
- For (a), the initial (elastic plus plastic) strain is the only strain suffered by the material.
- The elastic strain (ε_E) is recovered on unloading. In (b), strain increases with time.
- On unloading, only the initial elastic strain is recovered; the initial (time-independent) and time-dependent plastic strains are not.

Mechanical Behaviour of Materials, Thomas H. Courtney, Waveland Press Inc., 2005

Now we move on to some phenomenological description of creep. So creep is being looked at by several researchers in a very different angle so this is one phenomenological description which shows like this, what is this? This plot is again a strain versus time only but what is shown here is? One is time independent curve and time dependent curve so the difference between time independent curve that is time independent curve is (a) and the time dependent curve is (b). So you can see that this is a time dependent as the time increases you can also see that strain increases and in this curve the as the time increases nothing happens to the strength so it is time independent curve. The strain is plotted for a constant stress applied at t = 0 and held until the time t_1 at which it is removed. So after the time t_1 is reached the load is removed then what happens? Then obviously we will be able to recover some strain. So that is called elastic strike that is why it is called ε_E recoverable plastic strength time dependent elastic recoverable strength that is how you should understand this. Because even in intensive deformation we are looking at the recoverable string but that may not be kept for so long time as in the creep test so this is very important. So similarly you have the recoverable elastic strain and then a non-recoverable plastic strain. For a, the initial plastic plus elastic strain is the only strain suffered by the material and the elastic strain is recovered on unloading in b the strain increases with time. So this is one difference. So, here we are not talking about the strain is only the elastic plus plastic is shown here. But here it is not beyond that which is not possible all there are pure plastic strain.

On unloading only the initial elastic strain is recovered and the initial time dependent and time independent plastic strains or not so this is very important point that is why the whole plot is brought here. The initial time independent and the time dependent plastic I mean time independent strain is brought back and then time dependent plastic strains are not recoverable. So time dependent elastic strain something you can recover and time dependent plastic strain cannot be recovered that is the idea.

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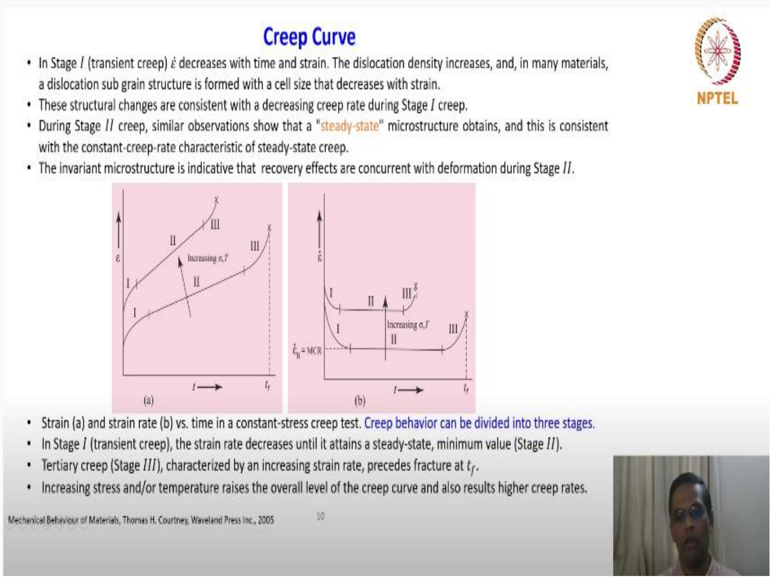

Creep Curve

- In Stage I (transient creep) $\dot{\varepsilon}$ decreases with time and strain. The dislocation density increases, and, in many materials, a dislocation sub grain structure is formed with a cell size that decreases with strain.
- These structural changes are consistent with a decreasing creep rate during Stage I creep.
- During Stage II creep, similar observations show that a "steady-state" microstructure obtains, and this is consistent with the constant-creep-rate characteristic of steady-state creep.
- The invariant microstructure is indicative that recovery effects are concurrent with deformation during Stage II.

- Strain (a) and strain rate (b) vs. time in a constant-stress creep test. Creep behavior can be divided into three stages.
- In Stage I (transient creep), the strain rate decreases until it attains a steady-state, minimum value (Stage II).
- Tertiary creep (Stage III), characterized by an increasing strain rate, precedes fracture at t_f.
- Increasing stress and/or temperature raises the overall level of the creep curve and also results higher creep rates.

Mechanical Behaviour of Materials, Thomas H. Courtney, Waveland Press Inc., 2005

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So little more insights to this creep curve like; I said that you know several researchers have looked at several aspects of the deformation and their influence and implications on the material behavior. In stage 1 which is also called transient creep strain rate decreases with time and strength the dislocation density increases because of the work hardening. And in many materials the dislocation sub grains structure is formed with the cell size that decreases with strain. So as the strain increases as a function of time people have observed that the cell size also decreases is one observation. These structural changes are consistent with decreasing creep rate during stage 1, 3. So now people are trying to understand what are the microstructural changes accompanying the each stage of the creep curve? During stage 2 similar observation shows that a steady state microstructure contains and this is consistent with the constant creep rate characteristic of steady state creep.

So the stage 2 is a constant creep rate characteristic that is what it is exhibiting and it also should have a typical microstructure what is the typical microstructure? The invariant microstructure is indicative that the recovery effects are concurrent with the deformation during stage two. So I just mentioned in the beginning any material which shows a steady state deformation behavior like this there could be two competing events that takes place. In this case work hardening as well as work softening. So, what hardening will multiply the dislocation and the recovery will annihilates them. So these two rates, I mean two reactions occur at the same rate. So then the steady state is reached and then the resultant microstructure invariant microstructure so that is very important. So only when the microstructure remains invariant then your deformation will not affect the materials life. So these are the two interesting plot to understand the influence of temperature and the stress on the creep stripe so this is a strain versus time plot again. And what you see is with the increasing the stress and temperature you can also see that the strain keep on increasing. On the other hand the creep rate versus time also shows a similar trend with increasing sigma and temperature your creep rate also becoming very high.

But you can see that the overall time to break is reduced as the temperature and stress is increasing. So this is what just I described here. So increasing stress and temperature raises the overall level of creep curve and also results in highest creep rate. So the overall improve, increases this the whole curve is shifted here that is what it means and then the rate also get higher.

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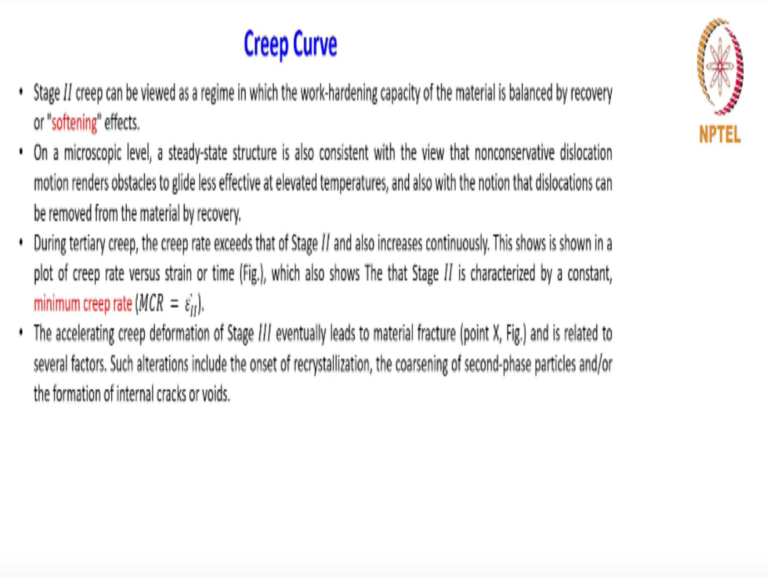

Creep Curve

- Stage II creep can be viewed as a regime in which the work-hardening capacity of the material is balanced by recovery or "softening" effects.
- On a microscopic level, a steady-state structure is also consistent with the view that nonconservative dislocation motion renders obstacles to glide less effective at elevated temperatures, and also with the notion that dislocations can be removed from the material by recovery.
- During tertiary creep, the creep rate exceeds that of Stage II and also increases continuously. This shows is shown in a plot of creep rate versus strain or time (Fig.), which also shows The that Stage II is characterized by a constant, minimum creep rate ($MCR = \dot{\varepsilon}_{II}$).
- The accelerating creep deformation of Stage III eventually leads to material fracture (point X, Fig.) and is related to several factors. Such alterations include the onset of recrystallization, the coarsening of second-phase particles and/or the formation of internal cracks or voids.

Stage 2, creep can be viewed as a regime in which the work hardening capacity of the material is balanced by recovery or softening effects, just I just mentioned. On a microscopic level a steady state structure is also consistent with the view that non-conservative dislocation motion renders obstacles to glide less effective at elevated temperatures. And also with the notion that dislocations can be removed from the material by the recovery. So it is what does it we are trying to say here?

We are talking about a steady state microstructure please understand that. So it has to be a non-conservative dislocation motion and there is obstacle to glide less effective so though the dislocation is moving you know at any direction. That is why it is called non-conservative motion it is not moving in any particular glide plane or any particular location. A non-conservative means it can move anywhere even though it moves but it provides you know motion renders obstacles to glide less effective.

So the obstacle to that kind of emotion is less effective at elevated temperature this is the point you have to understand. Then only that kind of a steady state can be maintained if you remember that if the all the dislocations are you know obstructed irrespective of the temperature then the steady state cannot reach so that is the point. At the same time the dislocation can be removed from the material by recovery.

So whatever the dislocation generated is also getting removed by recovery. So during tertiary claim the creep rate exceeds that of stage 2 and also increases continuously this shows sorry there is a typo error. This is shown in a plot of three plates versus strain at the time you will show the figure which also shows that stage 2 is characterized by constant creep rate that is we have already seen in the previous slide. The accelerating deformation of stage 3 eventually leads to material fracture as shown in the figure and this is related to several factors such alterations include onset of crystallization, the coarsening of second phase particles and formation of internal cracks and voids. This point I have already mentioned in the previous slide so it is only a redundant information here. So what is important is to understand the steady state microstructure?

What is happening and what makes it invariant microstructure? So that point you have to understand other than that these are all we have already seen.

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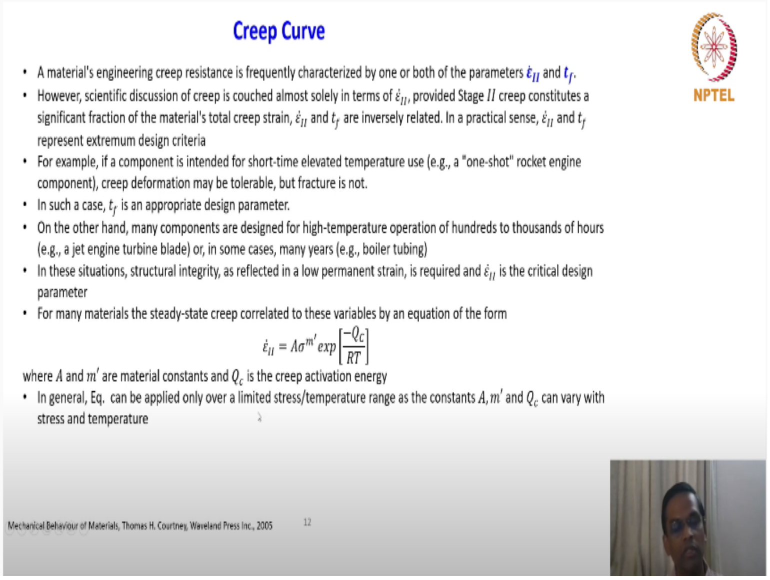

Creep Curve

- A material's engineering creep resistance is frequently characterized by one or both of the parameters $\dot{\varepsilon}_{II}$ and t_f.
- However, scientific discussion of creep is couched almost solely in terms of $\dot{\varepsilon}_{II}$, provided Stage II creep constitutes a significant fraction of the material's total creep strain, $\dot{\varepsilon}_{II}$ and t_f are inversely related. In a practical sense, $\dot{\varepsilon}_{II}$ and t_f represent extremum design criteria
- For example, if a component is intended for short-time elevated temperature use (e.g., a "one-shot" rocket engine component), creep deformation may be tolerable, but fracture is not.
- In such a case, t_f is an appropriate design parameter.
- On the other hand, many components are designed for high-temperature operation of hundreds to thousands of hours (e.g., a jet engine turbine blade) or, in some cases, many years (e.g., boiler tubing)
- In these situations, structural integrity, as reflected in a low permanent strain, is required and $\dot{\varepsilon}_{II}$ is the critical design parameter
- For many materials the steady-state creep correlated to these variables by an equation of the form

$$\dot{\varepsilon}_{II} = A\sigma^{m'} exp\left[\frac{-Q_C}{RT}\right]$$

where A and m' are material constants and Q_c is the creep activation energy

- In general, Eq. can be applied only over a limited stress/temperature range as the constants A, m' and Q_c can vary with stress and temperature

Mechanical Behaviour of Materials, Thomas H. Courtney, Waveland Press Inc., 2005

So a material’s engineering creep resistance is frequently characterized by one or both of the parameters that is here we are talking about creep rate that is $\dot{\varepsilon}_2$. That means a creep rate in at the steady state and t_f time to fracture these are the two parameters which are very useful in the engineering applications. However scientific discussion of creep is couched almost solely in terms of $\dot{\varepsilon}_2$, provided stage 2 creep constitutes a significant fraction of materials total creep strain. Please understand that what we are now trying to say here is we can talk about this, why this is important? Because these three constitute a significant fracture of materials total friction. So the total strain experienced by a material during complete deformation. The major portion of the strain I mean respective of stage 1, stage 2, stage 3 and stage 2 only accommodates huge amount of strength that is what it is? That is why this stage is important $\dot{\varepsilon}_2$ and t_f are inversely related please understand. These are all inversely related in a practical sense $\dot{\varepsilon}_2$ and t_f represent extreme design criteria. We will try to understand then why do we study this? If these 2 parameters that is important for example if a component is intended for a short time elevated temperature use for example a one shot rocket engine component creep deformation may be tolerable but fracture is not.

So that is why t_f is important time to fracture that parameter is important. Though it is not you know going to give an interesting creep deformation data but that time to fracture is very important. Because the component like you know one shot rocket engine component that means it is only used only one time and the time to fracture is more important than the creep strength in this application that is why this parameter is also studied.

In such a case t_f is an appropriate design parameter it is not a creep strain here it is t_f is the appropriate design parameter. On the other hand many components are designed for high temperature operation of hundreds to thousands of hours that is a jet engine turbine blade this is again very important. The jet engine turbine blade is going to be in use for you know hours and hours together you know they are going to keep on running and in such cases we need a creep data or in some cases many years a boiler tubing so jet engine turbine blade is one example; boiler tubing they are all going to subjected to high temperature and strain and for very long time to many years. So that is these are two classical examples which clearly bring out the importance of why the creep strain is important or time to fracture study is important.

In these situations structural integrity as reflected in a low permanent strain is required and $\dot{\varepsilon}_2$ is a critical design parameter. For many materials the steady state creep correlated to these variables by an equation of the form $\dot{\varepsilon}_2 = A\sigma^{m'} \exp[-Q_c/RT]$. So this is a very basic equation so you have to remember this is the steady state creep equation.

Whatever we are going to discuss quite a bit of creep deformation and their mechanisms so this is the basis all the equations will follow this format. Because we are talking about a steady state creep, where A, and m′ are material constants Q_c is the creep activation energy. So now we have a background to understand Q_c we the initial slides we have just discussed about how Q_c is perceived and how it is discussed so A, and m′ are material constants. In general the above equation can be applied only over a limited stress temperature range as the constants A and m′ and Q_c can vary with the stress and temperature you have to remember in creep is a strong function of stress temperature and strain rate. A combination of these parameters will suit for different materials at a different context. So this equation also will work for a limited stress and temperature range and because the other constants can vary with the temperature and stress.

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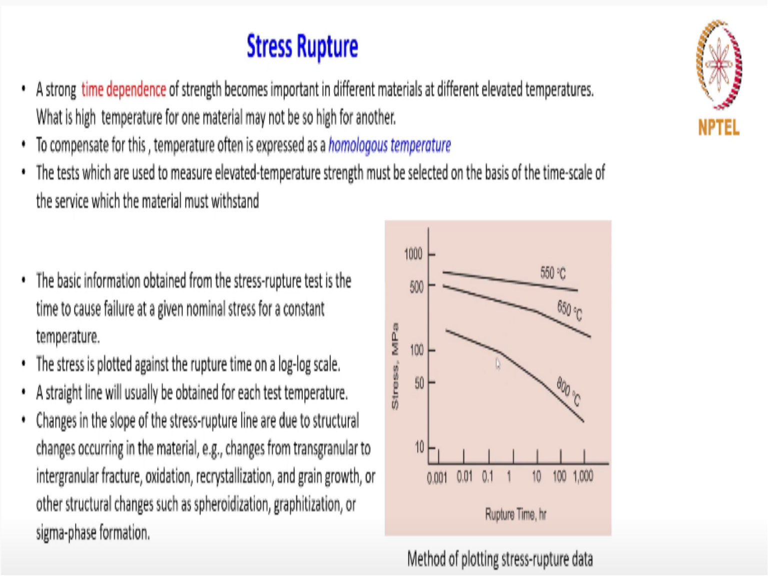

Stress Rupture

- A strong *time dependence* of strength becomes important in different materials at different elevated temperatures. What is high temperature for one material may not be so high for another.
- To compensate for this , temperature often is expressed as a *homologous temperature*
- The tests which are used to measure elevated-temperature strength must be selected on the basis of the time-scale of the service which the material must withstand

- The basic information obtained from the stress-rupture test is the time to cause failure at a given nominal stress for a constant temperature.
- The stress is plotted against the rupture time on a log-log scale.
- A straight line will usually be obtained for each test temperature.
- Changes in the slope of the stress-rupture line are due to structural changes occurring in the material, e.g., changes from transgranular to intergranular fracture, oxidation, recrystallization, and grain growth, or other structural changes such as spheroidization, graphitization, or sigma-phase formation.

Method of plotting stress-rupture data

There is something called stress rupture so similar way we discussed in the creep the stress rupture is also a very important deformation behavior at high temperatures. Like time to fracture that parameter comes only from this stress rupture test. So we are talking about creep test and the stress rupture test. And we have already discussed why the stress rupture test is important? Because there are applications where it is just one time use and then time to fracture is very important design parameter as compared to $\dot{\varepsilon}_2$ that is a steady state creep rate parameter. A strong time dependence of strength becomes important in different materials at different elevated temperatures which is high temperature for one material not be so high for another. To compensate this temperature often is expressed as homologous temperature. So now this explains why in all the creep literatures especially when we look at all you know temperature dependence we use something called homologous temperature. Just we want to avoid the influence of melting point, just avoid the influence of melting point and look at the temperature then you get the true effect of temperature. Because the high temperature for; one material may not be so high for the other material so homologous temperature is a normalized parameter to compare. The tests which, are used to measure elevated temperature strength must be selected on the basis of time scale of the service which the material must withstand. So we just looked at few examples like turbine blade in the jet engine and boiler tubes and jet rocket component and so on. So the stress rupture data is plotted like this stress versus rupture time so you can see that always you get a straight line like this for most of the test. And the basic information obtained from these stress structure test is the time to cause failure at a given nominal stress for a constant temperature. The stress is plotted against the rupture time on a log-log scale.

So you can see that a straight line will be usually be obtained for each test temperature so it is for every temperature there is a straight line but changes in the slope of the stress rupture line are due to structural changes occurring in the material. So you see that this is a simple straight line but on the other hand you have the change in slope takes place at 650 and then the change in slope takes place two times one here and another 800 so the changes from the trans granular to inter granular temperature fracture. So this also we talked about when we talk about ECG temperature trans-granular fracture to intermittent fracture. So oxidation recrystallization and brain growth or other structural changes such as fertilization graphization sigma phase formation and so on. So all these things can so this is also an indication of something happening into the material and when you see the slope change in the stress versus rupture time data.

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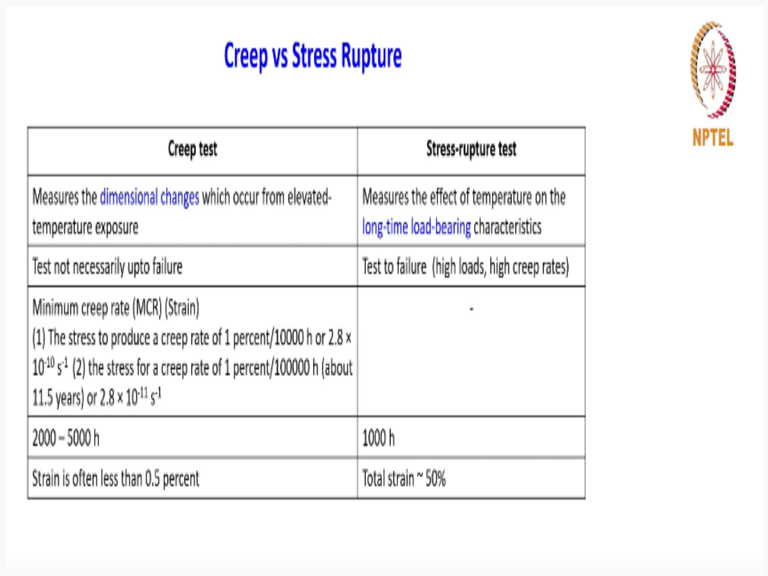

Creep vs Stress Rupture

Creep test	Stress-rupture test
Measures the dimensional changes which occur from elevated-temperature exposure	Measures the effect of temperature on the long-time load-bearing characteristics
Test not necessarily upto failure	Test to failure (high loads, high creep rates)
Minimum creep rate (MCR) (Strain) (1) The stress to produce a creep rate of 1 percent/10000 h or $2.8 \times 10^{-10}\ s^{-1}$ (2) the stress for a creep rate of 1 percent/100000 h (about 11.5 years) or $2.8 \times 10^{-11}\ s^{-1}$	-
2000 – 5000 h	1000 h
Strain is often less than 0.5 percent	Total strain ~ 50%

So what are the primary differences between these two? We are talking about a creep test and the rupture test. So I just tabulated just for the some key features in a creep test we measure I mean it measures the dimensional changes which occur from the eliminated temperature exposure. On the other hand stress rupture test measures the effect of temperature on the long term load bearing characteristics so this is very important.

Creep test not necessarily up to failure because we are only interested in steady state creep which is the design parameter. But here the test is to failure normally involves very high loads

and very high creep rates. Tertiary critical will cross and there is something called the minimum creep rate and MCR which is a design parameter. Which; is normally defined as the stress to produce a creep rate of 1% per 10,000 hours or 2.8× -10 per second.
Or the stress for the creep rate of 1% per one hundred thousand hours about 11.5 hours or 2.8×10^{-11} per second. So this is how the minimum creep rate is defined I mean in this order. So the typical time taken for you know creep tests is 2000 to 5000 hours but here it is just around 1000 hours. This total strain is often less than 0.5% in the creep tests and here it is nearly 50%.

So these are the primary difference between these two tests creep test and the stress rupture test. But then the purpose of measuring these parameters are quite different and which; also we have discussed elaborate. So now we will just discuss the creep mechanisms based upon the stress strain rate temperature combinations. There are different interesting mechanisms possible and it is not going to be the same mechanism for every material. We are going to talk about crystalline materials first and then we will go to a non-crystalline material and so on. So you will stop here today and then we will continue in the next lecture thank you.