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ENR116 Engineering Materials

Module 2 Material Properties

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Welcome to ENR116 Engineering Materials. This lecture summary is part of module 2, Material Properties. I’m Louise Smith and I will be presenting this lecture summary.

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This lecture summary is on fatigue and creep.

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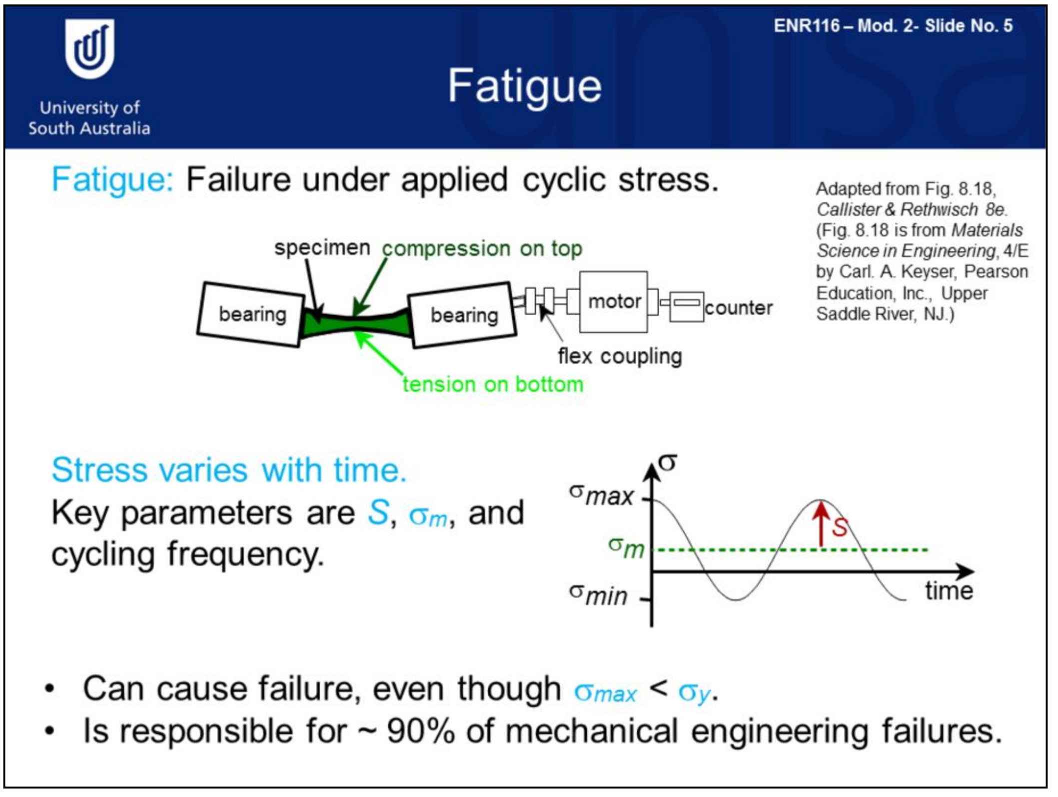
Intended Learning Outcomes

At the end of this section, students will be able to:-

- Identify the effects of repetitive stress on material components.
- Understand the effects of temperature and stress on component failure.

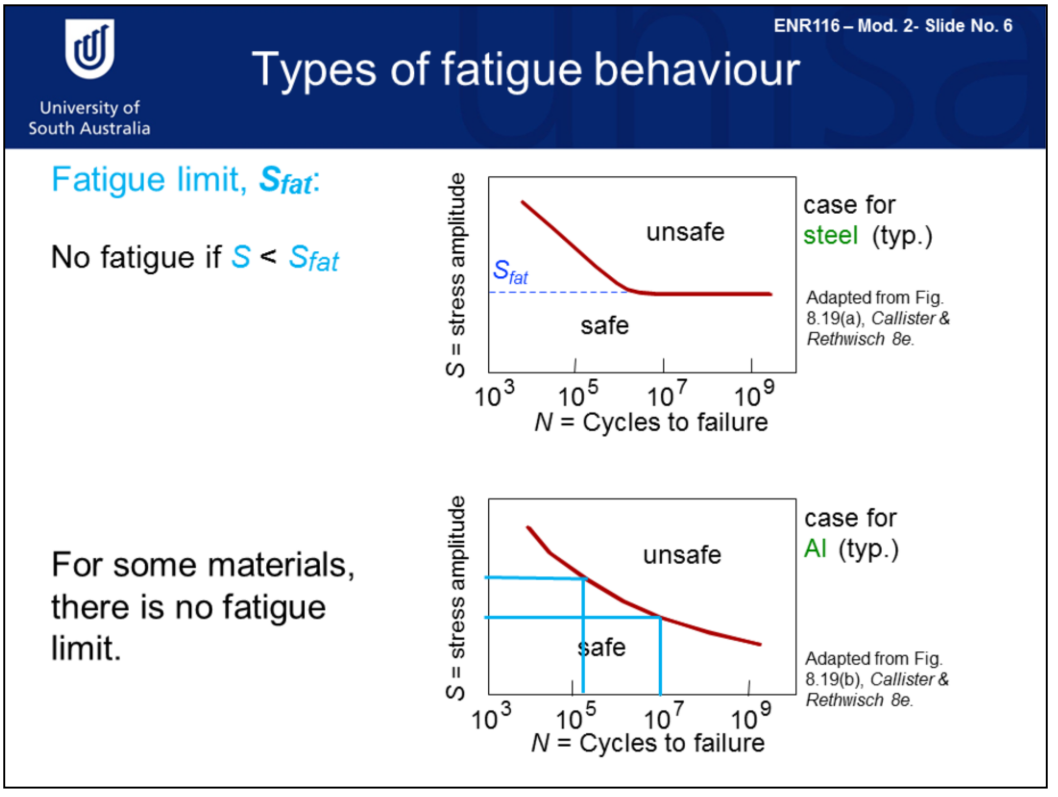
By the end of this lecture summary you will be able to identify the effects of repetitive stress on materials and understand how the temperature and stress affect component failure.



Fatigue is the failure of a material or component under an applied cyclic stress. It is a form of failure that occurs most often in dynamic structures. Structures that are experiencing dynamic and changing stresses. Examples of these kinds of structures are bridges, axels in vehicles, elevator cables and airplane components. The stress experienced by the material varies with time but it may be uniaxial tension or compression, flexural or torsional.

Key components in fatigue are the stress experienced by the specimen S and the mean stress experienced by the specimen sigma m as well as the cycling frequency.

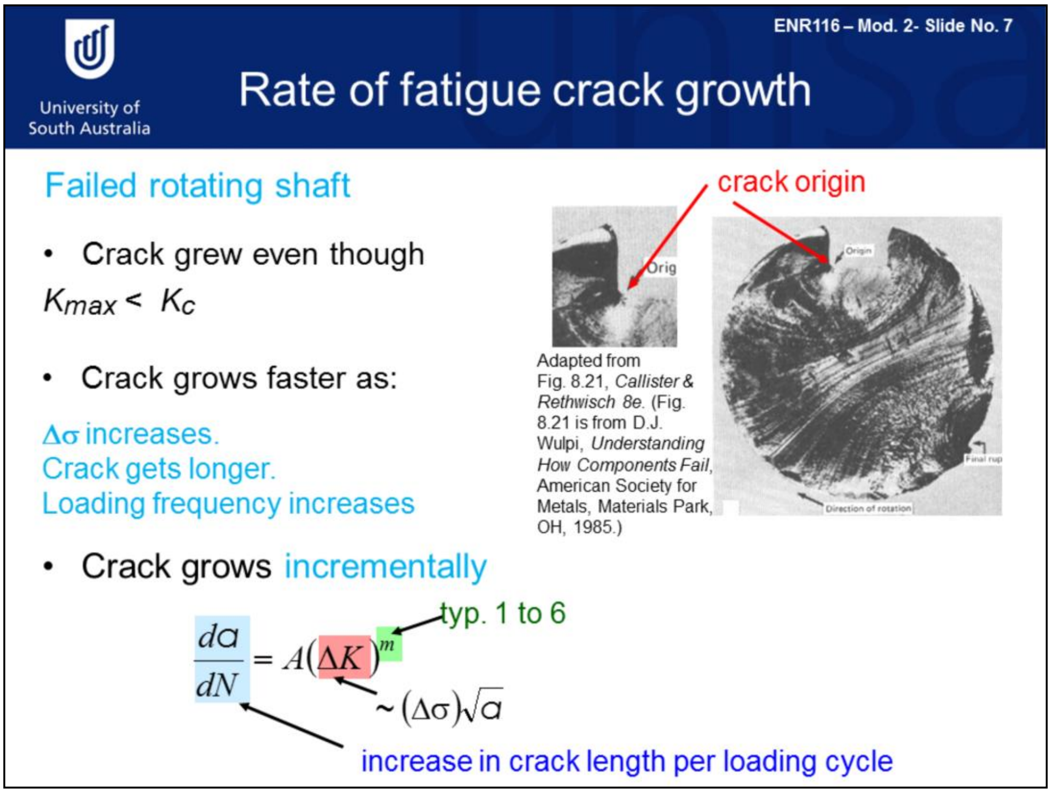
If we assume that this sine wave describes a testing regime, say a specimen loaded uniaxially. You can see that the stress experienced by the specimen is both tensile and slightly compressive and this fluctuates repeatedly with time. This results in a moderately tensile mean stress which is half the size of the maximum stress experienced by the material. This maximum stress might be below the yield strength of the material, however it can still result in the failure of the material. Fatigue is responsible for approximately 90% of mechanical engineering failures.



As with other material properties there are standard experiments, described by ASTM and ISO, performed to analyse the behaviour of materials when subjected to fatigue. These tests are performed by subjecting the material to the stress cycling at a relatively large percentage of the maximum stress. The stress used is normally about two thirds of the applied static tensile stress. The number of cycles to failure is counted and plotted as a S – N graph, where S us the amplitude of the applied stress and N is the number of cycles to failure. The number of cycles to failure is normally plotted using a logarithmic scale.

Some materials, such as iron and titanium based alloys there is a fatigue limit or endurance limit. This is when the S-N curve becomes horizontal at higher cycles to failure. Below this stress the material will not fail and therefore so long as the applied stress stays below the fatigue limit there will be no fatigue.

Some materials show no fatigue limit, examples of these materials are the non ferrous alloys. Alloys of metals like aluminium, copper and magnesium. Therefore for these materials failure will eventually occur due to fatigue regardless of the applied stress. These materials are therefore classified by their fatigue strength. This is defined as the stress level at which failure will occur for a specific number of cycles. You can see how this is calculated from the SN curve. A line is drawn up to the curve from a required number of cycles. The stress needed to fatigue the sample to this level is then read off. Another parameter that can be calculated from the SN curve is the fatigue life. Or N_f. This is the number of cycles to cause failure at a specific stress. So to calculate this you draw a line across from the applied stress to the SN curve and then see how many cycles this corresponds to. In this case failure due to fatigue will occur at just over 10 to the 5 or at just over 100,000 cycles.



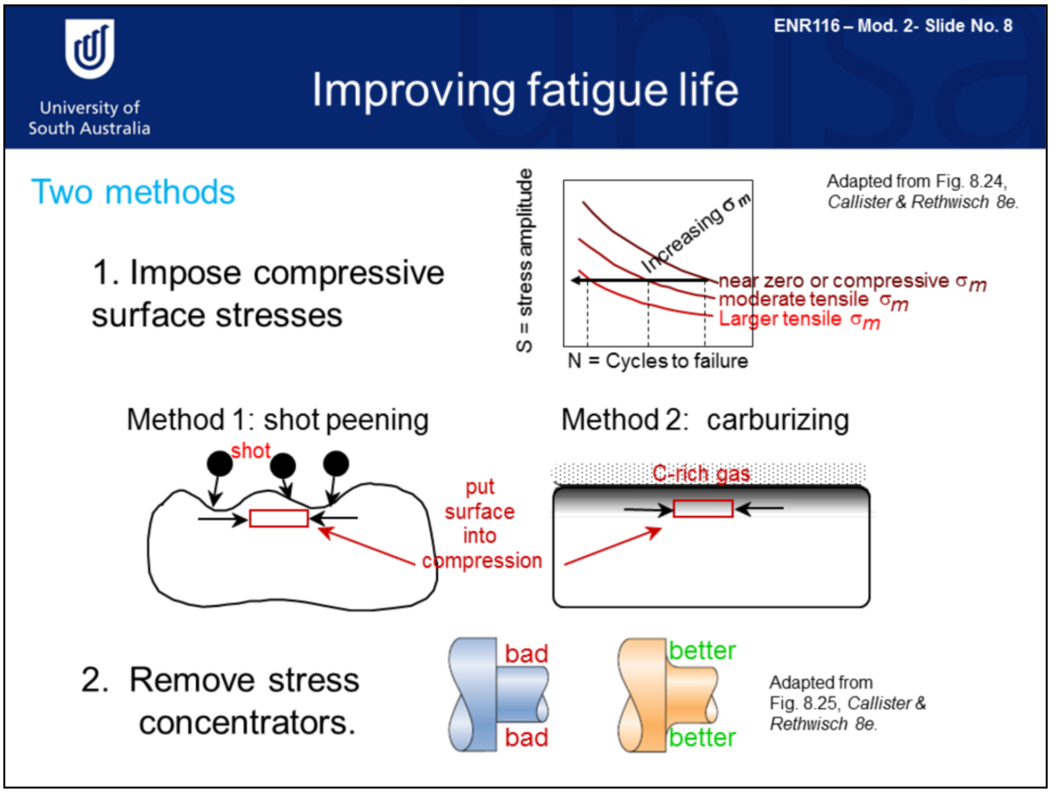
The failure of a component by fatigue can be broken down into three distinct steps. Crack initiation, crack propagation and final failure. During failure by fatigue cracks grow incrementally, increasing in length with each additional stress cycle during the crack propagation phase.

Once the crack has reached a critical length the crack propagates rapidly and failure occurs. Another way to describe the fatigue life is by adding the number of cycles during the crack growth and crack propagation phases together. The cycles that occur during the final failure stage are normally ignored as they are relatively small in number compared to the number of cycles needed for the first two phases.

The cracks that grow during fatigue are normally initiated on the surface of the material at a point of stress concentration. This stress concentrator can be due to a sharp change in the geometry of the specimen or due to microscopic cracks in the surface left over from the manufacture of the part. Once a crack has initiated it will initially propagate very slowly. As the crack slowly grows the crack tip is alternatively sharpened and blunted, change shape depending on the stage of the stress cycle. As a result the surfaces of components that have failed by fatigue have very definite striations.

Another characteristic of the fracture surface that points towards the crack initiation site is the presence of beachmarks or clamshell marks. If you look carefully at this micrograph you can see these marks surrounding the crack origin. They can also be seen extending through the material. This is typical in a material used in a component that experienced interruptions during the crack propagations. For example this rotating shaft that was part of a machine that only worked during normal working hours.

The crack grew and propagated through the material even though the stress intensity factor K is less than the fracture toughness of the material. Furthermore the crack grows quicker if the range of the applied stress is increased, as the crack grows longer and as the loading frequency increases. The crack will grow incrementally as the stress is cycled following this equation where dA/dN is the crack growth rate taken at some point on the S-N curve. This is equal to A, a material constant multiplied by delta K or the stress intensity factor at the crack tip raised to the power m which is another material constant, usually between 1 and 6.

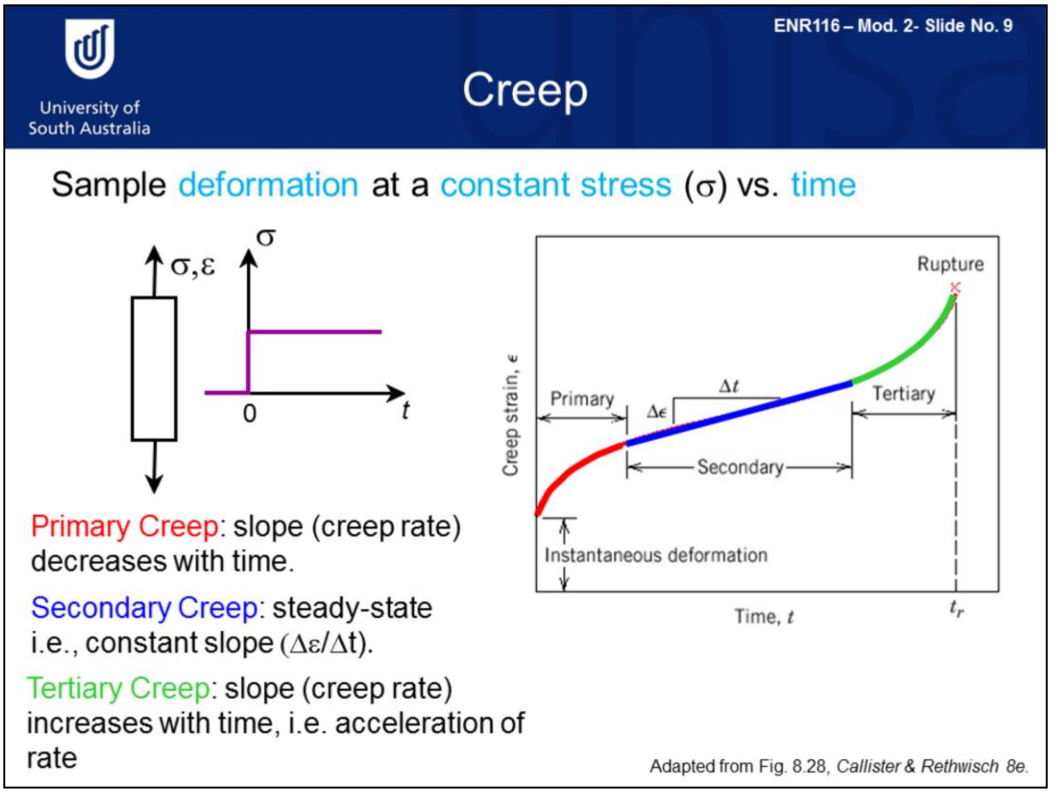


There are two main methods to improve the resistance of a material to fatigue. The first of these is to introduce compressive stress into the surface of the material to suppress crack growth.

One method of doing this is shot peening. This introduces a small amount of plastic deformation into the surface of the specimen. Small, hard particles or shot are fired onto the surface to be treated. These particles typically have diameters of 0.1 to 1mm. The compressive strain introduced into the material extends below the surface to a depth of between one quarter and one half the diameter of the shot particles.

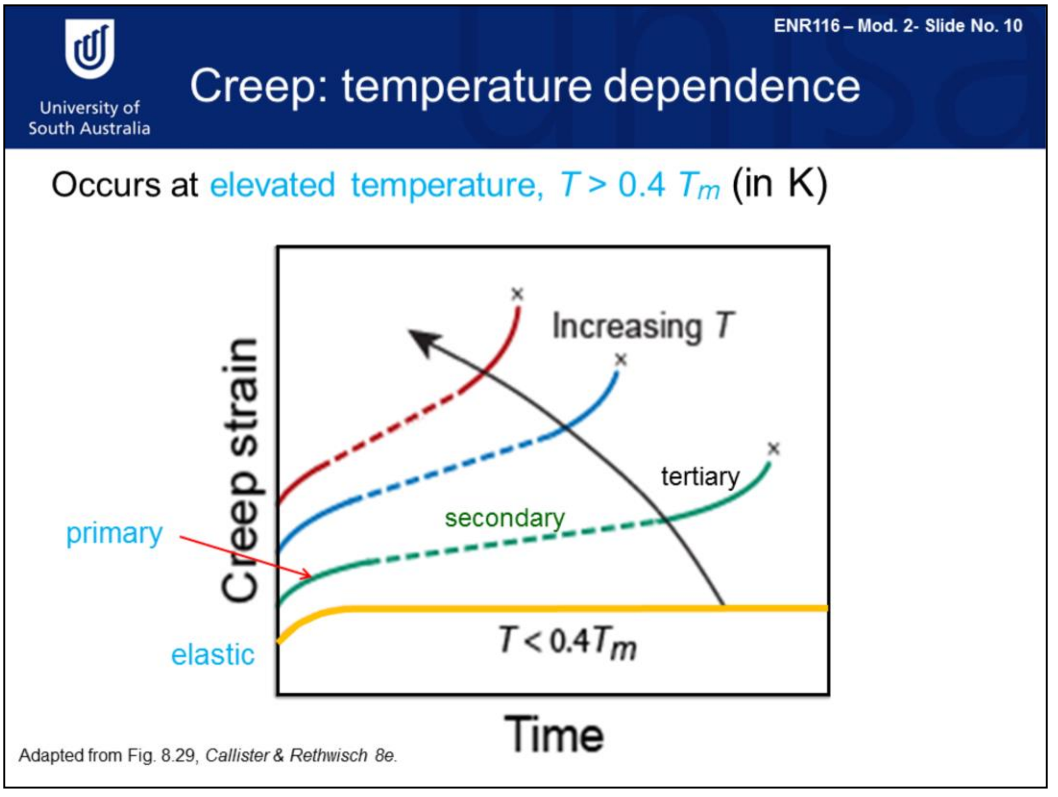
Another method of introducing compressive stress into the surface is by carburization or case hardening. The steel component is exposed to a carbonaceous or nitrogenous gas at an elevated temperature. The carbon, or nitrogen rich case so formed by the diffusion of the carbon or nitrogen into the metal is often about 1mm thick and is harder than the inner core of the material.

Another surface treatment is simply to polish the sample to remove larger cracks. The second method to improve the fatigue life of a component is to deign it with as few stress concentrators as possible.



Creep is defined as the permanent sample deformation observed a constant stress over time. Materials that that are often exposed to a constant stress over time will begin to deform. These materials are often exposed to high temperatures at the same time. Think of the turbine blades in an aircraft jet engine or high pressure steam lines. This is normally an undesirable process and will ultimately cause the component to fail. It is a phenomenon experienced by all materials, for metals it becomes an issue at working temperatures about 40% of their melting temperature. Amorphous polymers are especially vulnerable to creep. A typical creep test as described by ASTM standard E139 involves subjecting a specimen to a constant load or stress whilst maintaining a constant temperature.

The material deformation or strain is measured and plotted as a function of time. Most tests are the constant load tests rather than the constant stress tests. The creep curve produced by these tests has three distinct regions. Those of primary, secondary and tertiary creep. During primary creep the material exhibits strain hardening behaviour. During secondary creep, the material exhibits steady state creep, and in tertiary creep the creep rate accelerates and the component ruptures or fails.



Creep also has a strong dependence on temperature. For metals at temperatures below 40% of their melting temperature and after the initial elastic deformation seen in most materials the strain is almost independent of time. However at temperatures above 40% of their melting temperature the material creeps, and as the temperature is increased so the instantaneous strain at the time of the stress application increases. The steady state creep rate in the secondary creep phase increases and the creep lifetime is decreased.

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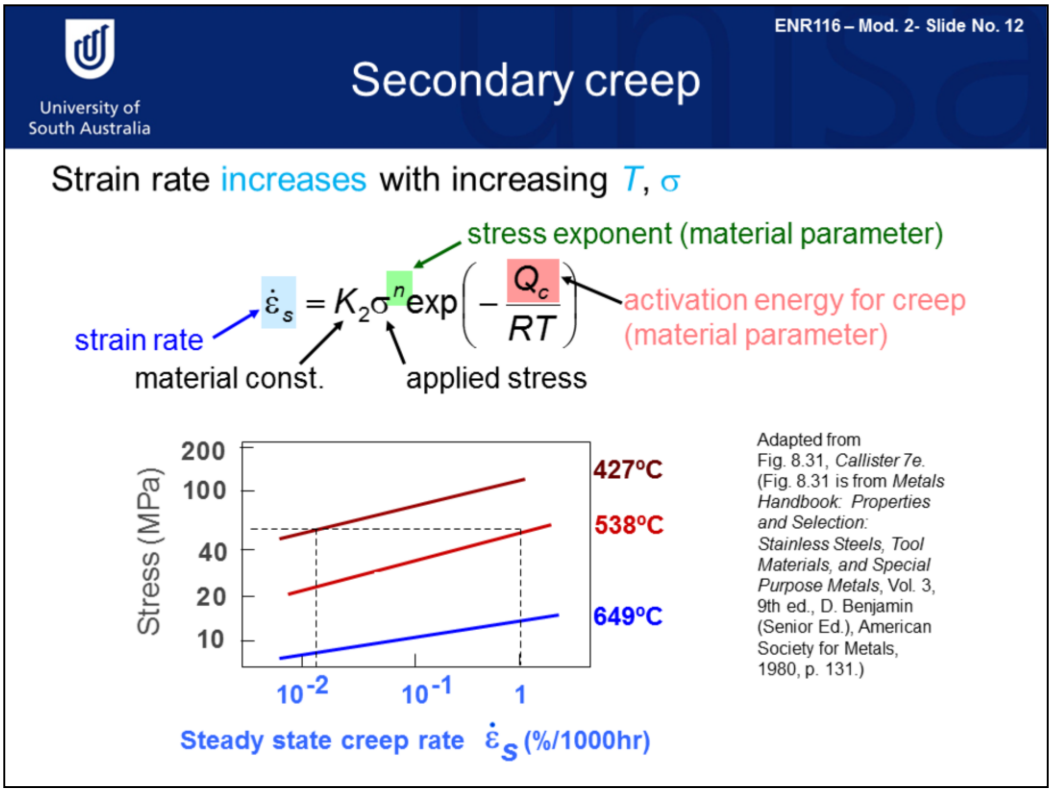
Secondary creep

Strain rate is constant at a given T, σ

Strain hardening is balanced by recovery

$$\exp\left(-\frac{\quad}{\quad}\right)$$

Equations describing the relationship between the stress and temperature as well as the steady state creep rate have been developed. In this equation for steady state or secondary creep the strain rate is equal to K sub script 2 which is a material constant multiplied by the applied stress to the power n where n is another material constant, the stress exponent. These parameters are then multiplied by the exponent of minus Qc or the activation energy for creep divided by the universal gas constant multiplied by the temperature.



To calculate n you need to plot the logarithm of the steady state creep strain rate against the applied stress. This yields a straight line with a gradient of n. It is also clear that this changes with the experimental temperature.

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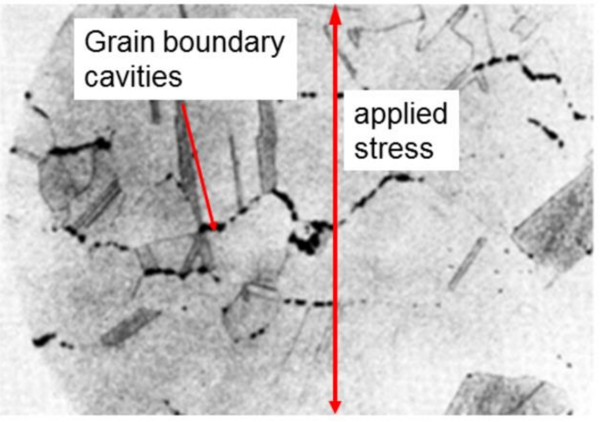
Creep failure

Failure: Along grain boundaries.



From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.32, p. 87, John Wiley and Sons, Inc., 1987. (Orig. source: Pergamon Press, Inc.)

When materials fail due to creep they tend to fail along the weakest part of the crystal structure, so along the grain boundaries. Normally in a direction that is perpendicular to that of the applied force. Therefore when designing components against creep, such as turbine blades carefully grown single crystals are used.

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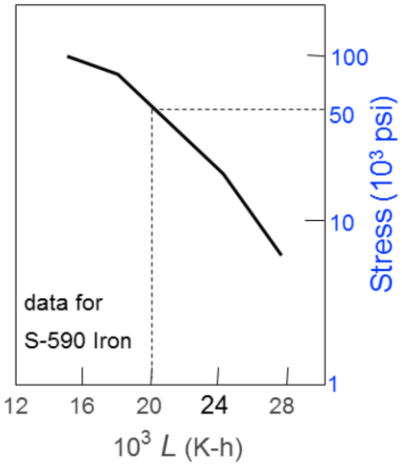
Prediction of creep rupture lifetime

Estimate rupture time:

S-590 Iron, T = 800ºC, σ = 50,000 psi



Adapted from Fig. 8.32, *Callister & Rethwisch 8e.* (Fig. 8.32 is from F.R. Larson and J. Miller, *Trans. ASME*, **74**, 765 (1952).)

Time to rupture, t_r

$$T(20 + \log t_r) = L$$

temperature

time to failure (rupture)

function of applied stress

Sometimes data is required that it is impractical to generate in the laboratory. In these cases the data is extrapolated from experiments performed for shorter times and / or at higher temperatures at a comparable stress level.

The Larson-Miller parameter is then used to estimate the time to rupture. Where T is temperature multiplied by a constant which is normally 20 which has been added to the logarithm of tr of the rupture lifetime in hours.

This can also be plotted as a graph. By working through this example of s-590 iron. The component is working at a temperature of 800 degrees centigrade, experiencing a stress of 50,000 pounds per square inch.

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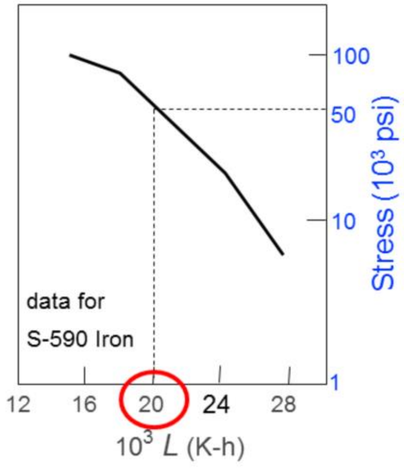
Worked example



$$(1073\ K)(20+\log t_r) = 20\times10^3$$

$$20+\log t_r = \frac{20\times10^3}{1073} = 18.639$$

$$\log t_r = 18.639 - 20 = -1.361$$

$$t_r = 10^{-1.361} = 0.044 \text{ hours}$$

Adapted from Fig. 8.32, *Callister & Rethwisch 8e.* (Fig. 8.32 is from F.R. Larson and J. Miller, *Trans. ASME*, **74**, 765 (1952).)

We can calculate L by using the data provided and the graph and we can see that The Larson-Miller parameter is 20,000. 800°C is equal to 1073K. Therefore 20+log t_r multiplied by the temperature in Kelvin is equal to 20,000.

To solve this for time divide 20,000 by the temperature in Kelvin to get 20 plus log t_r is equal to 18.639. To isolate the log minus 20 from each side of the equation which results in log t_r being equal to -1.361. The log is then solved and the answer is 0.044 hours or 2.64 minutes or 2 minutes 38 seconds. If you look at the worked example for the same material at the same temperature in the course text book you can see that by increasing the applied stress the fatigue lifetime has been reduced from 233 hours to just over 2 and a half minutes. This is something to be wary of then using logarithmic scales. A small change on the logarithmic scale can result in a large change on a non logarithmic scale.

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Summary

- The type of failure depends on T and σ
- Simple fracture, failure stress decreases with:
  - increased maximum flaw size,
  - decreased T,
  - increased rate of loading.
- For fatigue (cyclic σ): cycles to fail decreases as $\Delta\sigma$ increases.
- For creep ($T > 0.4T_m$): time to rupture decreases as σ or T increases.

So in summary, the type of failure that a material will undergo ductile, moderately ductile, brittle, fatigue or creep depends on the temperature of the system as well as the applied stress. In a simple fracture system the stress needed to cause failure decreases with an increased maximum flaw size, decreased temperature and an increased rate of loading.

For a material experiencing fatigue the number of cycles needed to cause failure decrease as the applied cyclic stress increases.

Creep will occur at temperatures greater than 40% of the material melting temperature. The time to rupture or fatigue lifetime decreases as either or both the applied stress and temperature increase.

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Thank you

Thank you for your attention during this lecture summary. The concepts covered in this lecture summary are covered in chapter eight of the course text book as well as in the online resources. If you have any questions please post them on the message board.