Chapter Outline: Failure

How do Materials Break?

- **Ductile vs. brittle fracture**
- **Principles of fracture mechanics**
  - ✓ Stress concentration
- **Impact fracture testing**
- **Fatigue** (cyclic stresses)
  - ✓ Cyclic stresses, the S—N curve
  - ✓ Crack initiation and propagation
  - ✓ Factors that affect fatigue behavior
- **Creep** (time dependent deformation)
  - ✓ Stress and temperature effects
  - ✓ Alloys for high-temperature use

Not tested: *in 8.5 Fracture Toughness*
8.14 Data extrapolation methods

Fracture

Fracture: separation of a body into pieces due to stress, at temperatures below the melting point.

Steps in fracture:
- crack formation
- crack propagation

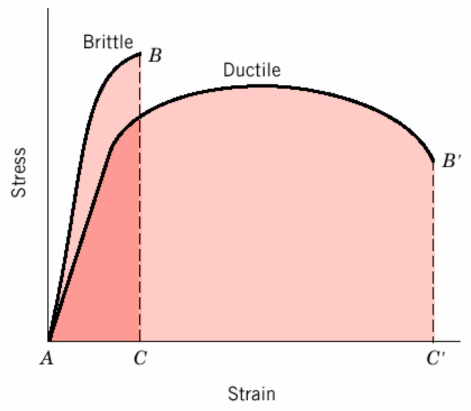
Depending on the ability of material to undergo plastic deformation before the fracture two fracture modes can be defined - **ductile or brittle**

- **Ductile fracture** - most metals (not too cold):
  - Extensive plastic deformation ahead of crack
  - Crack is "stable": resists further extension unless applied stress is increased
- **Brittle fracture** - ceramics, ice, cold metals:
  - Relatively little plastic deformation
  - Crack is "unstable": propagates rapidly without increase in applied stress

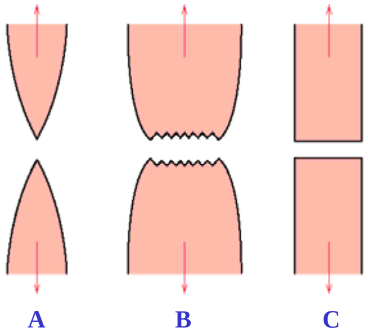
Ductile fracture is preferred in most applications

Brittle vs. Ductile Fracture

- **Ductile materials** - extensive plastic deformation and energy absorption ("toughness") before fracture
- **Brittle materials** - little plastic deformation and low energy absorption before fracture



Brittle vs. Ductile Fracture

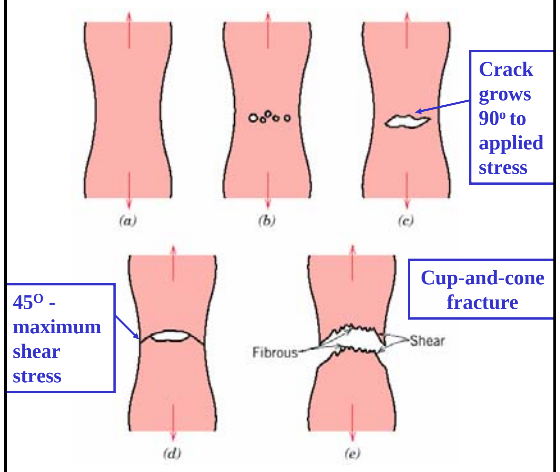


A. **Very ductile**, soft metals (e.g. Pb, Au) at room temperature, other metals, polymers, glasses at high temperature.

B. **Moderately ductile fracture**, typical for ductile metals

C. **Brittle fracture,** cold metals, ceramics.

Ductile Fracture (Dislocation Mediated)



Crack grows 90° to applied stress

Cup-and-cone fracture

45° - maximum shear stress

(a) Necking

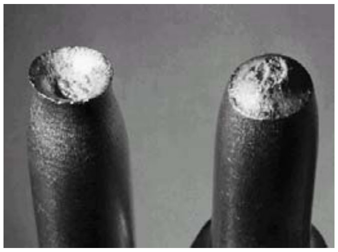
(b) Formation of microvoids

(c) Coalescence of microvoids to form a crack

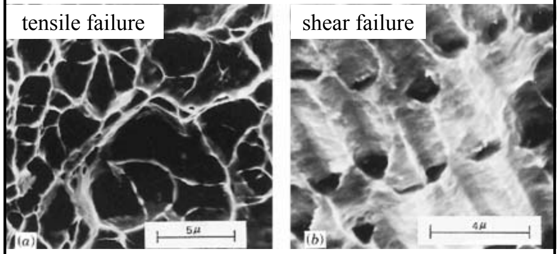
(d) Crack propagation by shear deformation

(e) Fracture

Ductile Fracture



(Cup-and-cone fracture in Al)

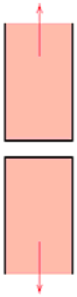


tensile failure

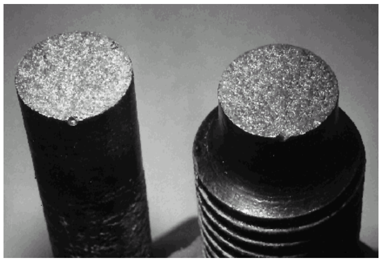
shear failure

Scanning Electron Microscopy: *Fractographic* studies at high resolution. Spherical “dimples” correspond to microvoids that initiate crack formation.

Brittle Fracture (Limited Dislocation Mobility)



- No appreciable plastic deformation
- Crack propagation is very fast
- Crack propagates nearly perpendicular to the direction of the applied stress
- Crack often propagates by cleavage - breaking of atomic bonds along specific crystallographic planes (cleavage planes).

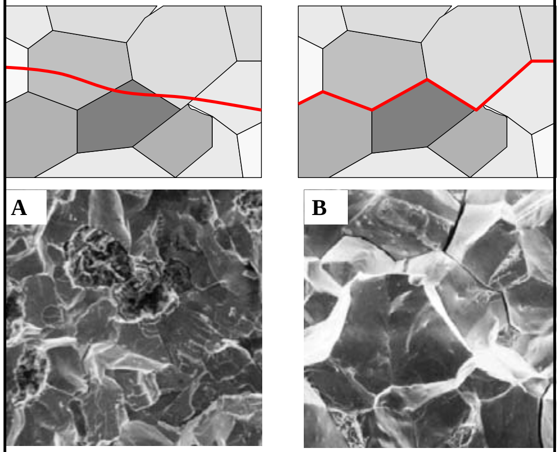


Brittle fracture in a mild steel

Brittle Fracture

A. Transgranular fracture: Fracture cracks pass through grains. Fracture surface have faceted texture because of different orientation of cleavage planes in grains.

B. Intergranular fracture: Fracture crack propagation is along grain boundaries (grain boundaries are weakened or embrittled by impurities segregation etc.)



Stress Concentration

Fracture strength of a brittle solid is related to the cohesive forces between atoms. One can estimate that the theoretical cohesive strength of a brittle material should be ~ E/10. But experimental fracture strength is normally E/100 - E/10,000.

This much lower fracture strength is explained by the effect of **stress concentration** at microscopic flaws. The applied stress is amplified at the tips of micro-cracks, voids, notches, surface scratches, corners, etc. that are called **stress raisers.** The magnitude of this amplification depends on micro-crack orientations, geometry and dimensions.

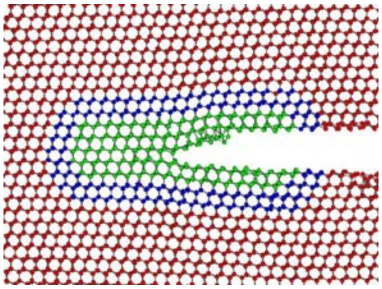
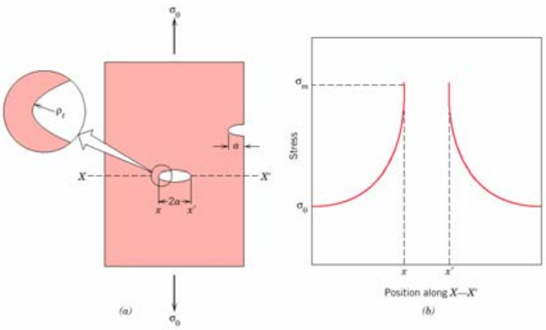


Figure by
N. Bernstein &
D. Hess, NRL

Stress Concentration



For a long crack oriented perpendicular to the applied stress the maximum stress near the crack tip is:

$$\sigma_m \approx 2\sigma_0 \left(\frac{a}{\rho_t}\right)^{1/2}$$

where $\boldsymbol{\sigma_0}$ is the applied external stress, **a** is the half-length of the crack, and $\boldsymbol{\rho_t}$ the radius of curvature of the crack tip. (note that **a** is half-length of the internal flaw, but the full length for a surface flaw).

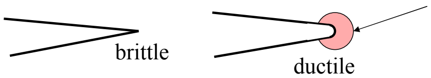
The **stress concentration factor** is: $K_t = \frac{\sigma_m}{\sigma_0} \approx 2\left(\frac{a}{\rho_t}\right)^{1/2}$

Crack propagation

Cracks with sharp tips propagate easier than cracks having blunt tips

$$\sigma_m \approx 2\sigma_0 \left(\frac{a}{\rho_t}\right)^{1/2}$$

In ductile materials, plastic deformation at a crack tip "blunts" the crack.



Energy balance on the crack

Elastic strain energy:

- energy stored in material as it is elastically deformed
- this energy is released when the crack propagates
- creation of new surfaces requires energy

Critical stress for crack propagation: $\sigma_c = \left(\frac{2E\gamma_s}{\pi a}\right)^{1/2}$

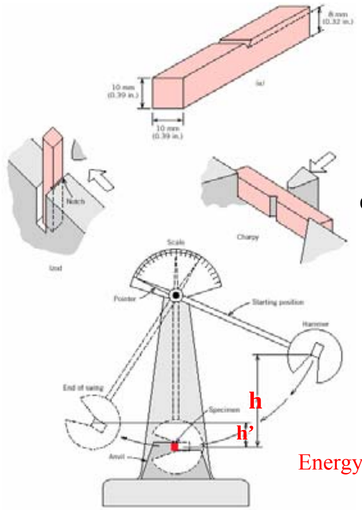
γ_s = specific surface energy **Griffith's criterion**

for ductile materials γ_s should be replaced with $\gamma_s + \gamma_p$
where γ_p is plastic deformation energy

Impact Fracture Testing

(testing fracture characteristics under high strain rates)

Two standard tests, the **Charpy** and **Izod,** measure the **impact energy** (the energy required to fracture a test piece under an impact load), also called the notch toughness.



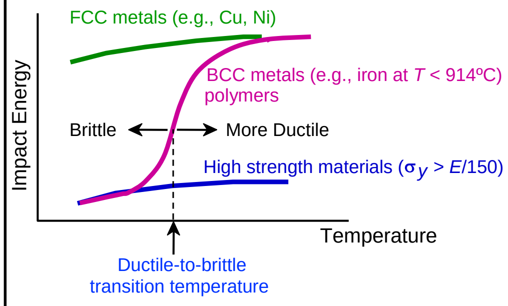
Energy ~ h - h'

Ductile-to-brittle transition

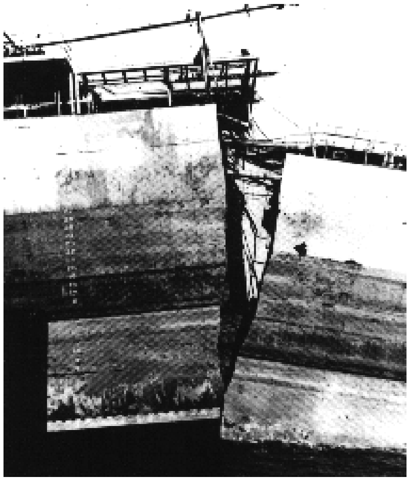
As temperature decreases a ductile material can become brittle - ductile-to-brittle transition

Alloying usually increases the ductile-to-brittle transition temperature. FCC metals remain ductile down to very low temperatures. For ceramics, this type of transition occurs at much higher temperatures than for metals.

The ductile-to-brittle transition can be measured by impact testing: the impact energy needed for fracture drops suddenly over a relatively narrow temperature range – temperature of the ductile-to-brittle transition.



Ductile-to-brittle transition

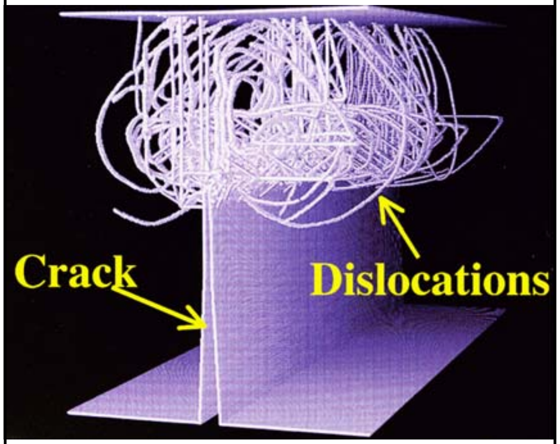


Low temperatures can severely embrittle steels. The Liberty ships, produced in great numbers during the WWII were the first all-welded ships. A significant number of ships failed by catastrophic fracture. Fatigue cracks nucleated at the corners of square hatches and propagated rapidly by brittle fracture.

"Dynamic" Brittle-to-Ductile Transition *(not tested)*

(from molecular dynamics simulation of crack propagation)

Ductile



Brittle

V. Bulatov et al., Nature 391, #6668, 669 (1998)

Fatigue

(Failure under fluctuating / cyclic stresses)

Under fluctuating / cyclic stresses, failure can occur at loads considerably lower than tensile or yield strengths of material under a static load: **Fatigue**

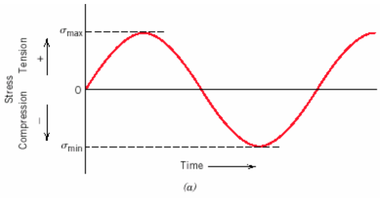
Estimated to causes 90% of all failures of metallic structures (bridges, aircraft, machine components, etc.)

Fatigue failure is brittle-like (relatively little plastic deformation) - even in normally ductile materials. Thus sudden and catastrophic!

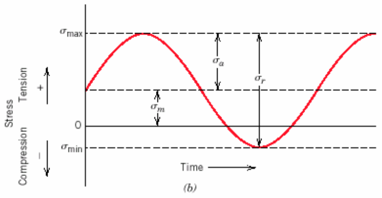
Applied stresses causing fatigue may be axial (tension or compression), flextural (bending) or torsional (twisting).

Fatigue failure proceeds in three distinct stages: crack initiation in the areas of stress concentration (near stress raisers), incremental crack propagation, final catastrophic failure.

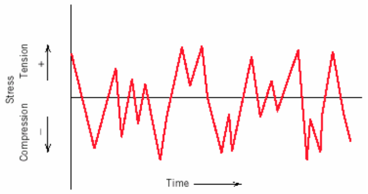
Fatigue: Cyclic Stresses (I)



Periodic and symmetrical about zero stress



Periodic and asymmetrical about zero stress



Random stress fluctuations

Fatigue: Cyclic Stresses (II)

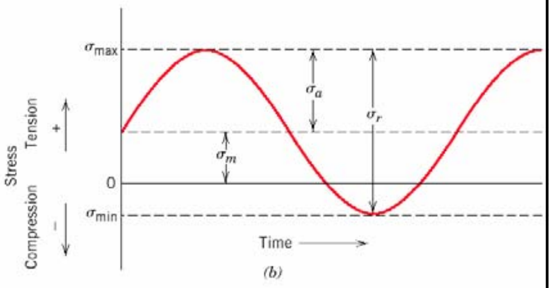
Cyclic stresses are characterized by maximum, minimum and mean stress, the range of stress, the stress amplitude, and the stress ratio

Mean stress: $\sigma_m = (\sigma_{max} + \sigma_{min}) / 2$

Range of stress: $\sigma_r = (\sigma_{max} - \sigma_{min})$

Stress amplitude: $\sigma_a = \sigma_r/2 = (\sigma_{max} - \sigma_{min}) / 2$

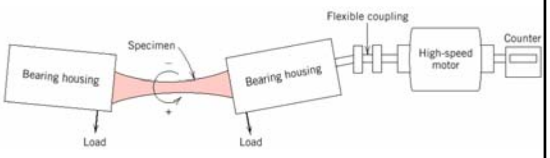
Stress ratio: $R = \sigma_{min} / \sigma_{max}$



Remember the convention that tensile stresses are positive, compressive stresses are negative

Fatigue: S — N curves (I)
(stress — number of cycles to failure)

Fatigue properties of a material (S-N curves) are tested in rotating-bending tests in fatigue testing apparatus:

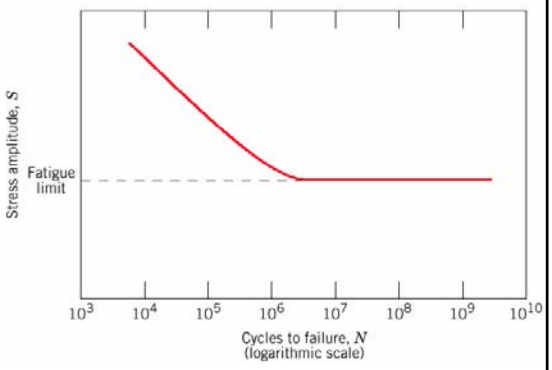


Result is commonly plotted as S (stress) vs. N (number of cycles to failure)

Low cycle fatigue: high loads, plastic and elastic deformation

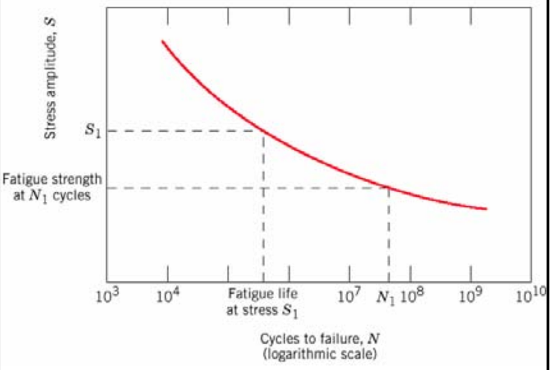
High cycle fatigue: low loads, elastic deformation (N > 10^5)

Fatigue: S—N curves (II)



Fatigue limit (endurance limit) occurs for some materials (e.g. some Fe and Ti alloys). In this case, the S—N curve becomes horizontal at large N. The fatigue limit is a maximum stress amplitude below which the material never fails, no matter how large the number of cycles is.

Fatigue: S—N curves (III)



In most alloys, S decreases continuously with N. In this cases the fatigue properties are described by

Fatigue strength: stress at which fracture occurs after a specified number of cycles (e.g. 10^7)

Fatigue life: Number of cycles to fail at a specified stress level

Fatigue: Crack initiation and propagation (I)

Three stages of fatigue failure:

1. crack initiation in the areas of stress concentration (near stress raisers)
2. incremental crack propagation
3. final rapid crack propagation after crack reaches critical size

The total number of cycles to failure is the sum of cycles at the first and the second stages:

$$N_f = N_i + N_p$$

N_f: Number of cycles to failure
N_i: Number of cycles for crack initiation
N_p : Number of cycles for crack propagation

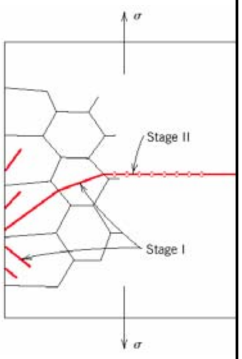
High cycle fatigue (low loads): N_i is relatively high. With increasing stress level, N_i decreases and N_p dominates

Fatigue: Crack initiation and propagation (II)

- Crack initiation at the sites of stress concentration (microcracks, scratches, indents, interior corners, dislocation slip steps, etc.). Quality of surface is important.
- Crack propagation

➢ Stage I: initial slow propagation along crystal planes with high resolved shear stress. Involves just a few grains, and has flat fracture surface

➢ Stage II: faster propagation perpendicular to the applied stress. Crack grows by repetitive blunting and sharpening process at crack tip. Rough fracture surface.



- Crack eventually reaches critical dimension and propagates very rapidly

Factors that affect fatigue life

- Magnitude of stress (mean, amplitude...)
- Quality of the surface (scratches, sharp transitions).

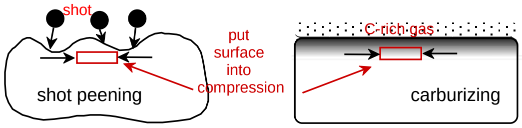
Solutions:

➢ Polishing (removes machining flaws etc.)

➢ Introducing compressive stresses (compensate for applied tensile stresses) into thin surface layer by "Shot Peening"- firing small shot into surface to be treated. High-tech solution - ion implantation, laser peening.

➢ Case Hardening - create C- or N- rich outer layer in steels by atomic diffusion from the surface. Makes harder outer layer and also introduces compressive stresses

➢ Optimizing geometry - avoid internal corners, notches etc.



Factors that affect fatigue life: environmental effects

- **Thermal Fatigue.** Thermal cycling causes expansion and contraction, hence thermal stress, if component is restrained.

  Solutions:

  - eliminate restraint by design
  - use materials with low thermal expansion coefficients

- **Corrosion fatigue.** Chemical reactions induce pits which act as stress raisers. Corrosion also enhances crack propagation.

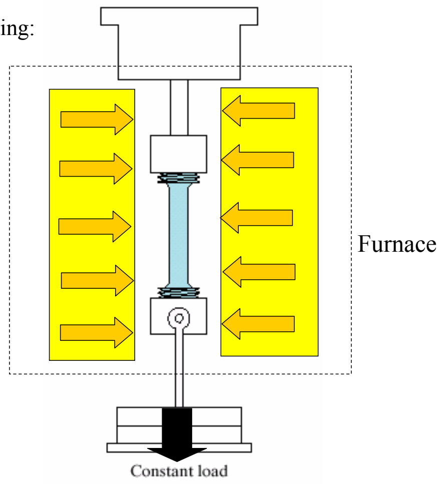
  Solutions:

  - decrease corrosiveness of medium, if possible
  - add protective surface coating
  - add residual compressive stresses

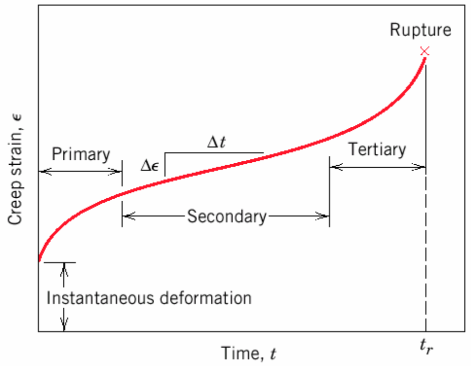
Creep

Creep is a **time-dependent and permanent** deformation of materials when subjected to a constant load at a **high temperature** (> 0.4 T_m). Examples: turbine blades, steam generators.

Creep testing:



Stages of creep

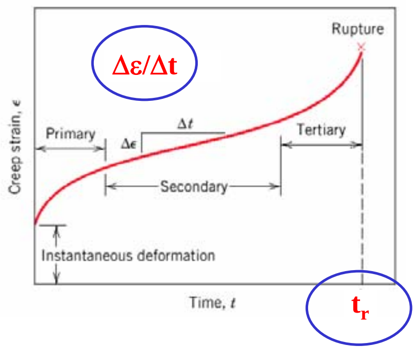


1. **Instantaneous deformation**, mainly elastic.
2. **Primary/transient creep**. Slope of strain vs. time decreases with time: work-hardening
3. **Secondary/steady-state creep**. Rate of straining is constant: balance of work-hardening and recovery.
4. **Tertiary.** Rapidly accelerating strain rate up to failure: formation of internal cracks, voids, grain boundary separation, necking, etc.

Parameters of creep behavior

The stage of secondary/steady-state creep is of longest duration and the **steady-state creep rate** $\dot{\varepsilon}_s = \Delta\varepsilon / \Delta t$ is the most important parameter of the creep behavior in long-life applications.

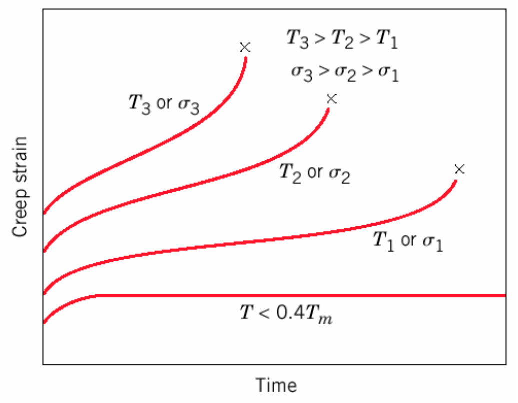
Another parameter, especially important in short-life creep situations, is **time to rupture, or the rupture lifetime, t_r.**



Creep: stress and temperature effects

With increasing stress or temperature:

- The instantaneous strain increases
- The steady-state creep rate increases
- The time to rupture decreases



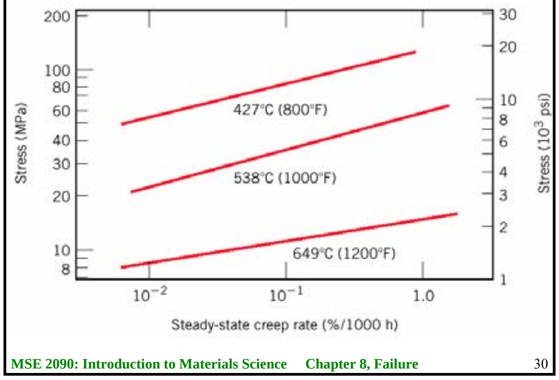
Creep: stress and temperature effects

The stress/temperature dependence of the steady-state creep rate can be described by

$$\dot{\varepsilon}_s = K_2\sigma^n \exp\left(-\frac{Q_c}{RT}\right)$$

where Q_c is the activation energy for creep, K_2 and n are material constants.

(Remember the Arrhenius dependence on temperature for thermally activated processes that we discussed for diffusion)

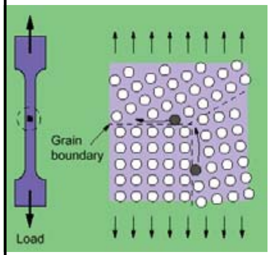


Mechanisms of Creep

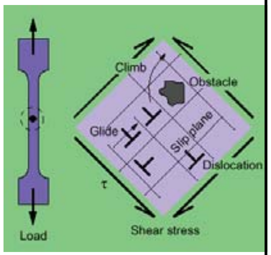
Different mechanisms are responsible for creep in different materials and under different loading and temperature conditions. The mechanisms include

- Stress-assisted vacancy diffusion
- Grain boundary diffusion
- Grain boundary sliding
- Dislocation motion

Different mechanisms result in different values of n, Q_c.



Grain boundary diffusion



Dislocation glide and climb

Alloys for high-temperature use

(turbines in jet engines, hypersonic airplanes, nuclear reactors, etc.)

Creep is generally minimized in materials with:

- ✓ High melting temperature
- ✓ High elastic modulus
- ✓ Large grain sizes (inhibits grain boundary sliding)

Following alloys are especially resilient to creep:

- ✓ Stainless steels
- ✓ Refractory metals (containing elements of high melting point, like Nb, Mo, W, Ta)
- ✓ “Superalloys” (Co, Ni based: solid solution hardening and secondary phases)

Summary

Make sure you understand language and concepts:

- Brittle fracture
- Corrosion fatigue
- Creep
- Ductile fracture
- Ductile-to-brittle transition
- Fatigue
- Fatigue life
- Fatigue limit
- Fatigue strength
- Impact energy
- Intergranular fracture
- Stress raiser
- Thermal fatigue
- Transgranular fracture

Reading for next class:

Chapter 9: Phase diagrams

- Fundamental concepts and language
- Phases and microstructure
- Binary isomorphous systems (complete solid solubility)
- Binary eutectic systems (limited solid solubility)
- Binary systems with intermediate phases/compounds
- The iron-carbon system (steel and cast iron)