Chapter 8 Failure

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Chapter Outline

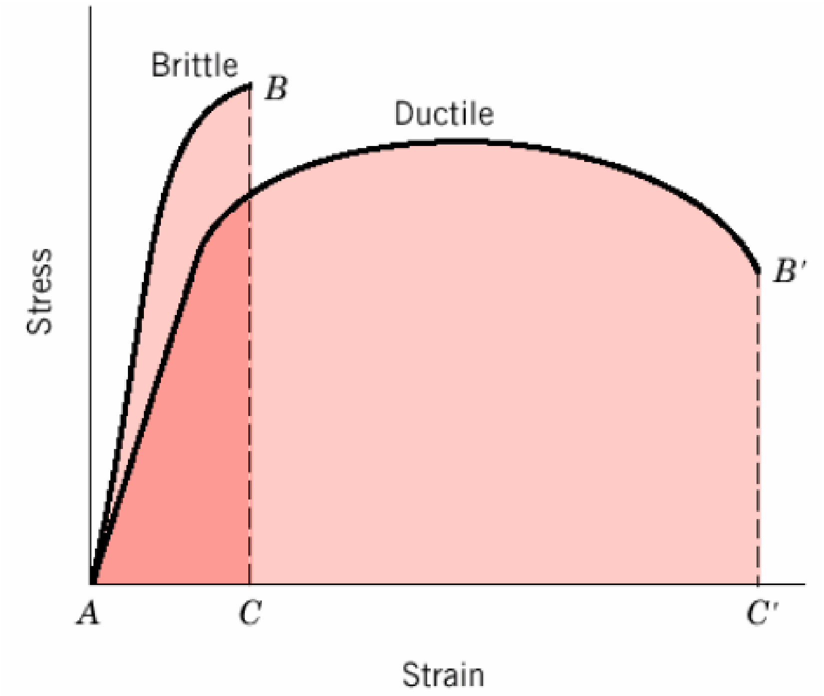
- **Ductile vs. brittle fracture**
- **Principles of fracture mechanics**
  - ✓ Stress concentration
- **Impact fracture testing**
- **Fatigue (cyclic stresses)**
  - ✓ Cyclic stresses, the S—N curve
  - ✓ Crack initiation and propagation
  - ✓ Factors that affect fatigue behavior
- **Creep (time dependent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

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

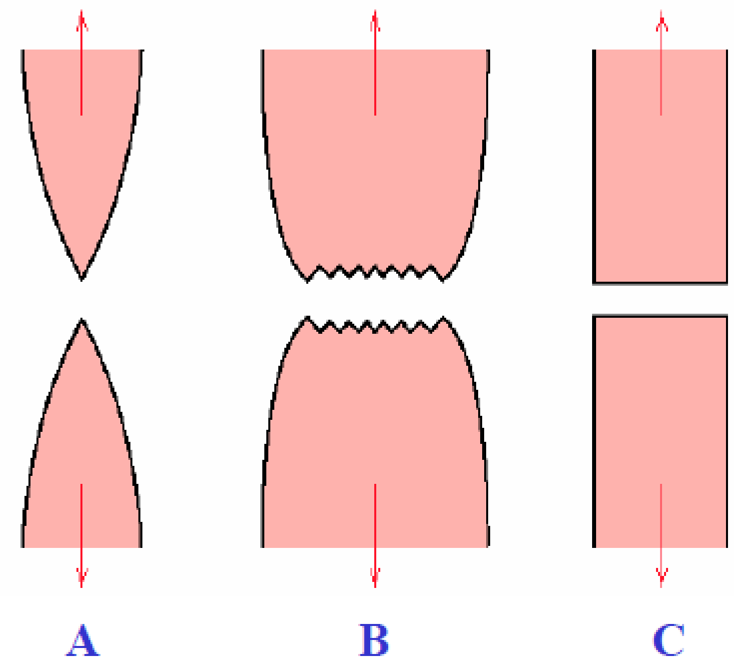


Brittle vs. Ductile Fracture

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

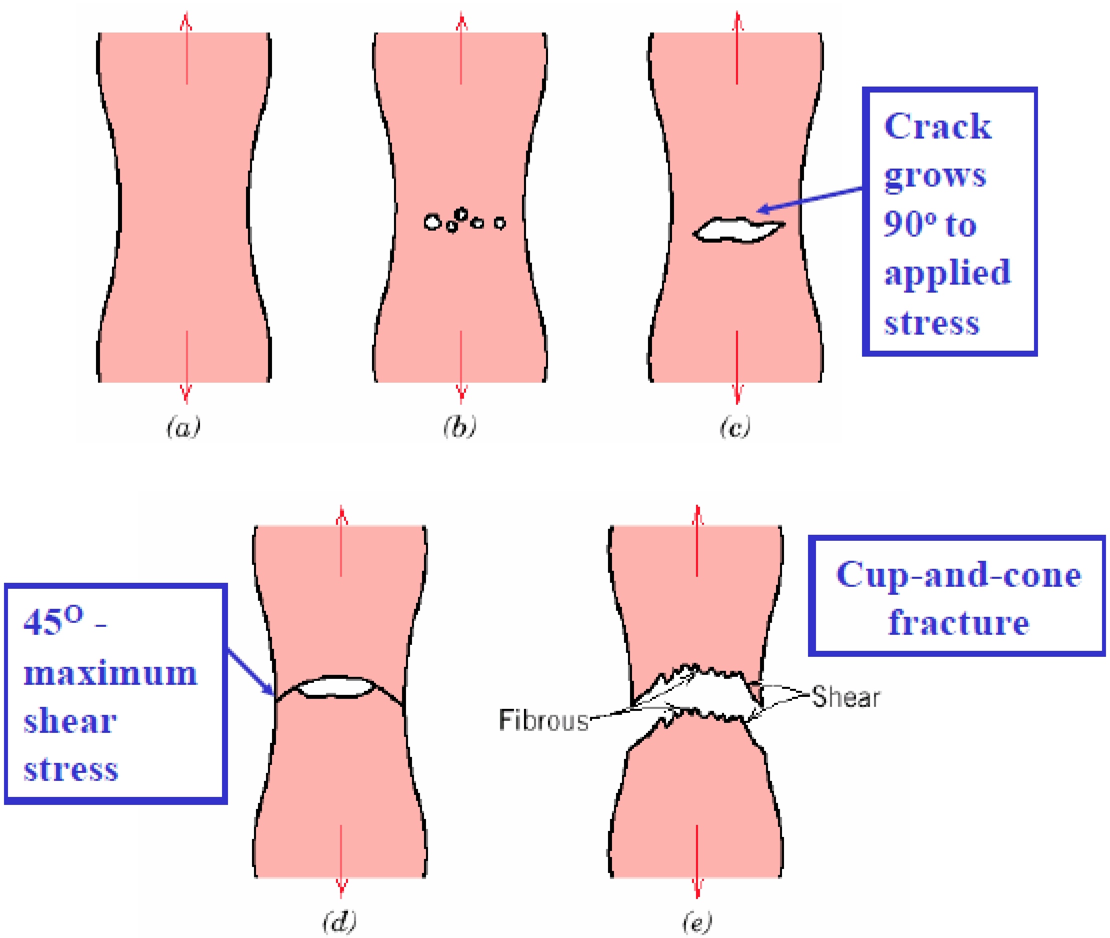
B. **Moderately ductile fracture, typical for ductile metals**

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

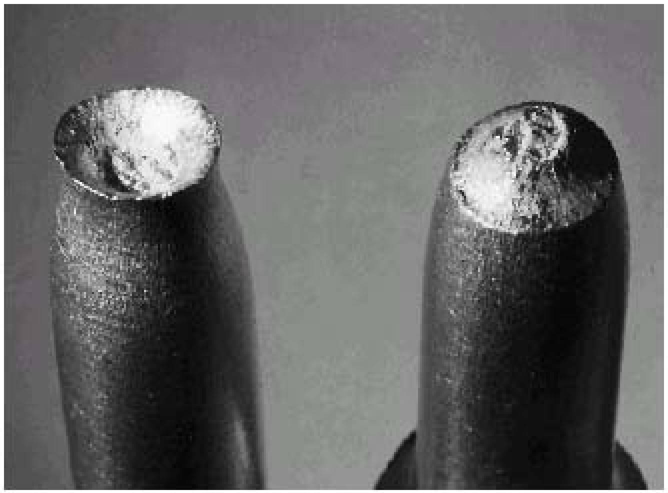


Ductile Fracture (Dislocation Mediated)

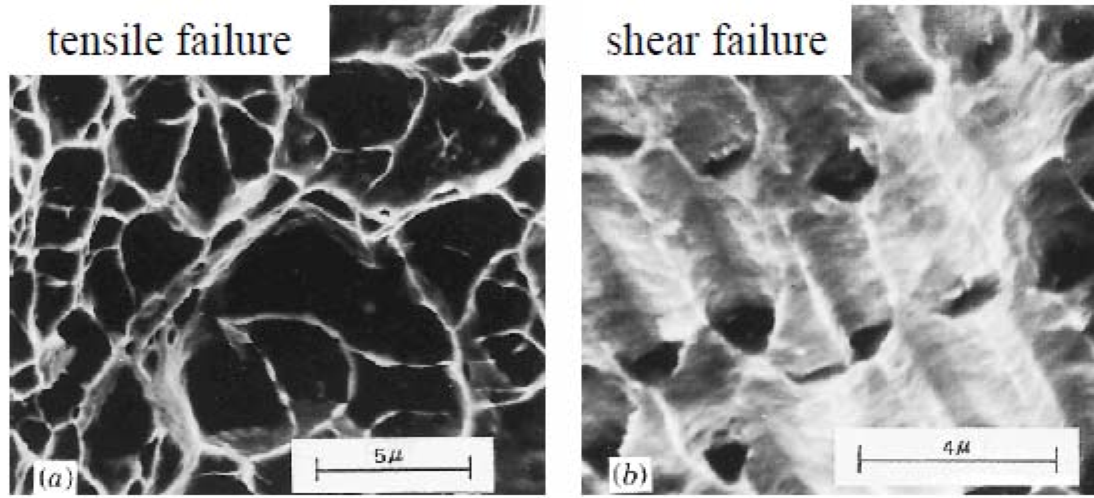
(a) Necking
(b) Formation of microvoids
(c) Coalescence of microvoids to form a crack
(d) Crack propagation by shear deformation
(e) Fracture



Ductile Fracture



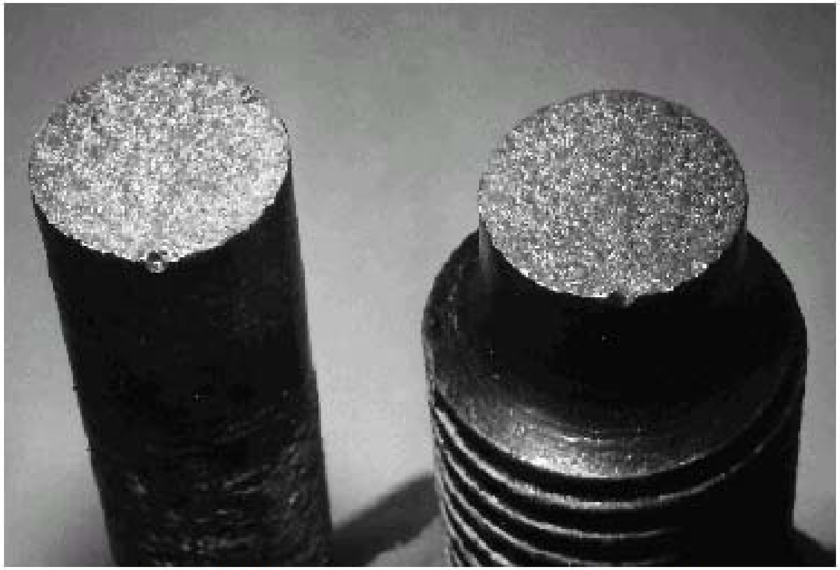
(Cup-and-cone fracture in Al)



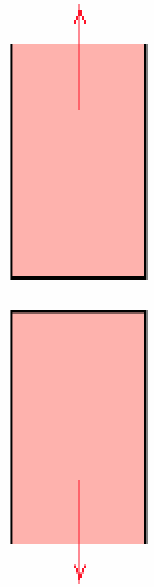
Scanning Electron Microscopy:
Fractographic studies at high resolution.
Spherical "dimples" correspond to
microvoids that initiate crack formation.

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).



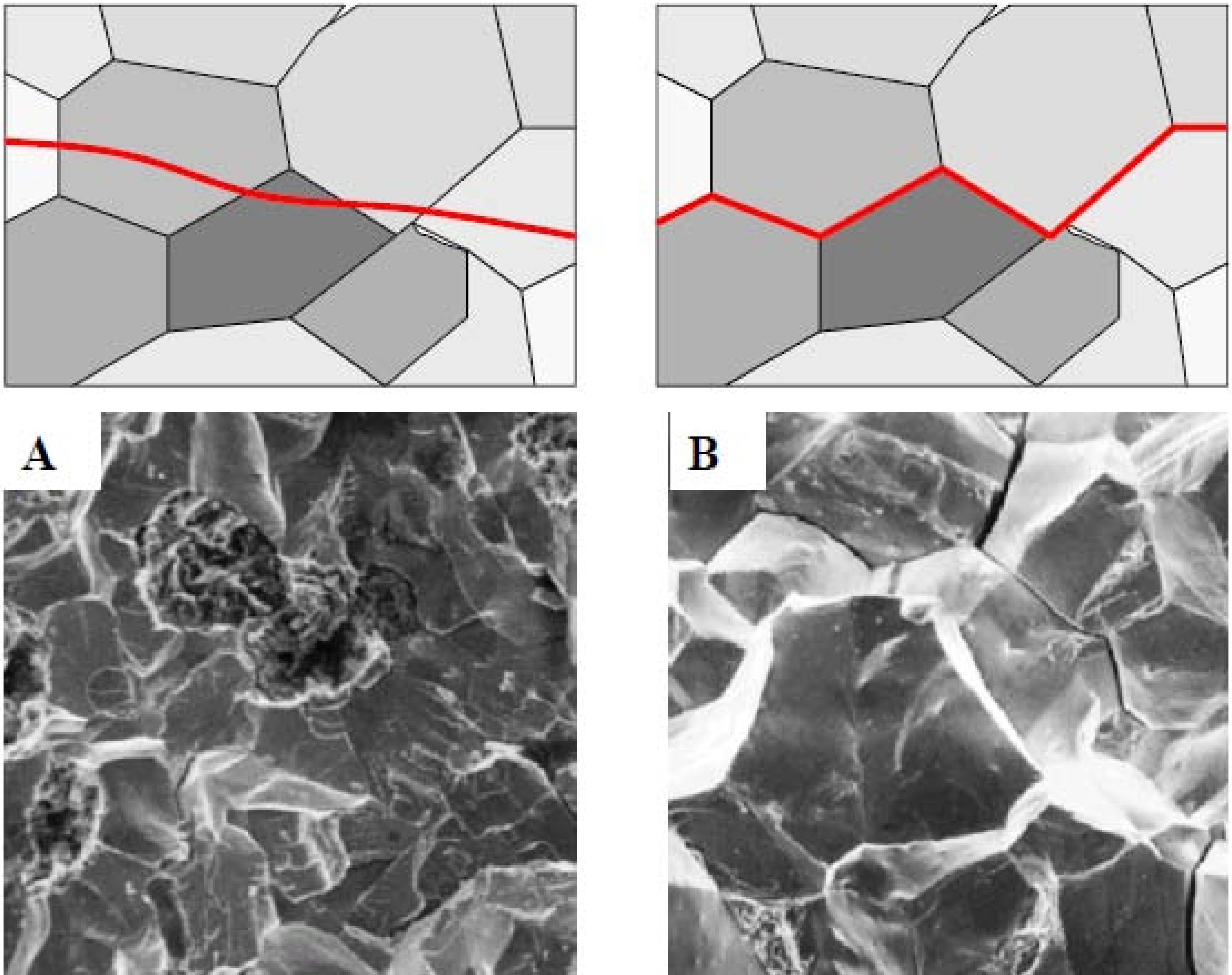
Brittle fracture in a mild steel



Brittle Fracture

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

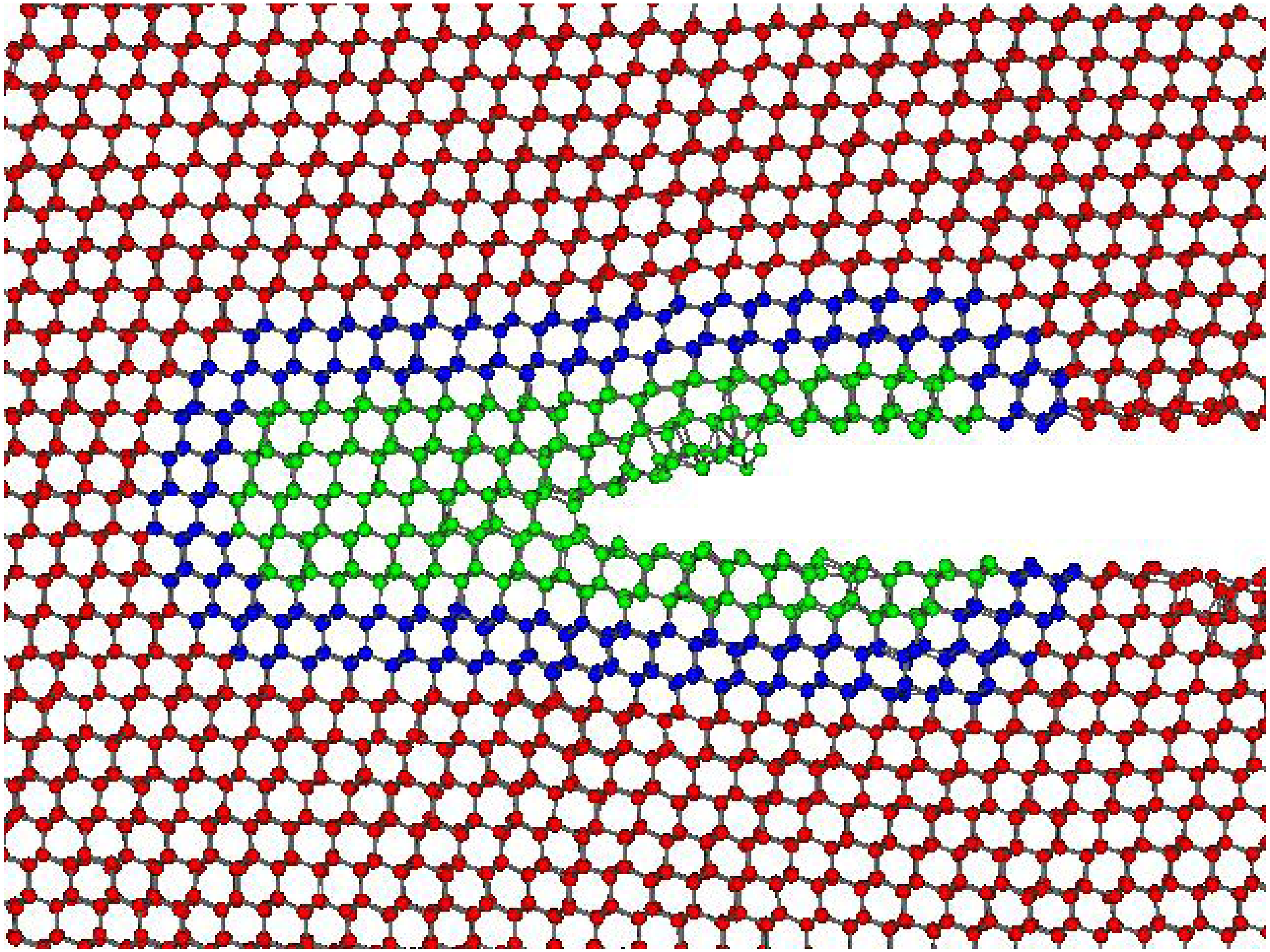
B. **Intergranular fracture: Fracture crack propagation is** along grain boundaries (grain boundaries are weakened or embrittled by impurities segregation etc.)


A
B

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.

Stress Concentration

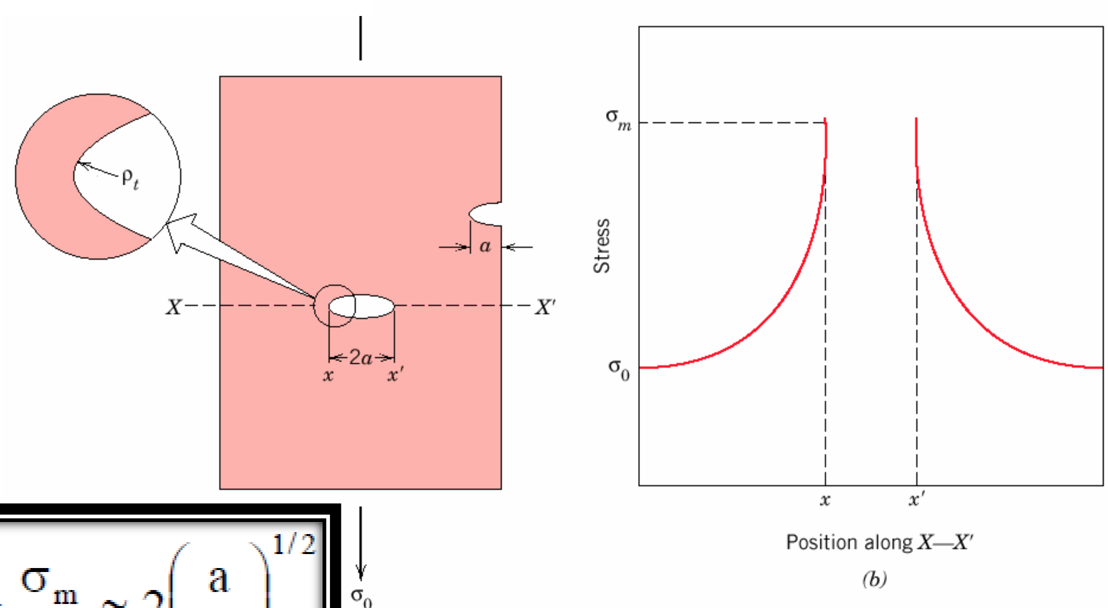


Stress Concentration

- 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 σ_0 **is the applied external stress, a is the half-length** of the crack, and ρ_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).



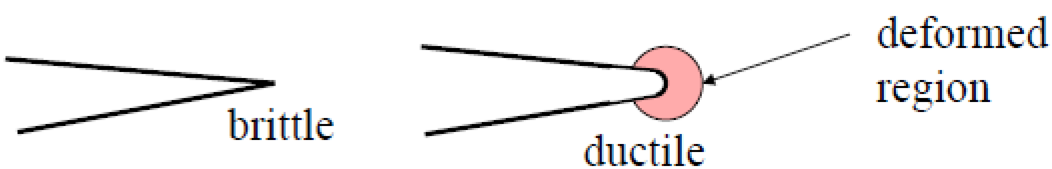
The **stress concentration factor** is: $K_t = \frac{\sigma_m}{\sigma_0} \approx 2\left(\frac{a}{\rho_t} \right)^{1/2}$

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:

$$\sigma_c = \left(\frac{2E\gamma_s}{\pi a}\right)^{1/2}$$

Griffith's criterion

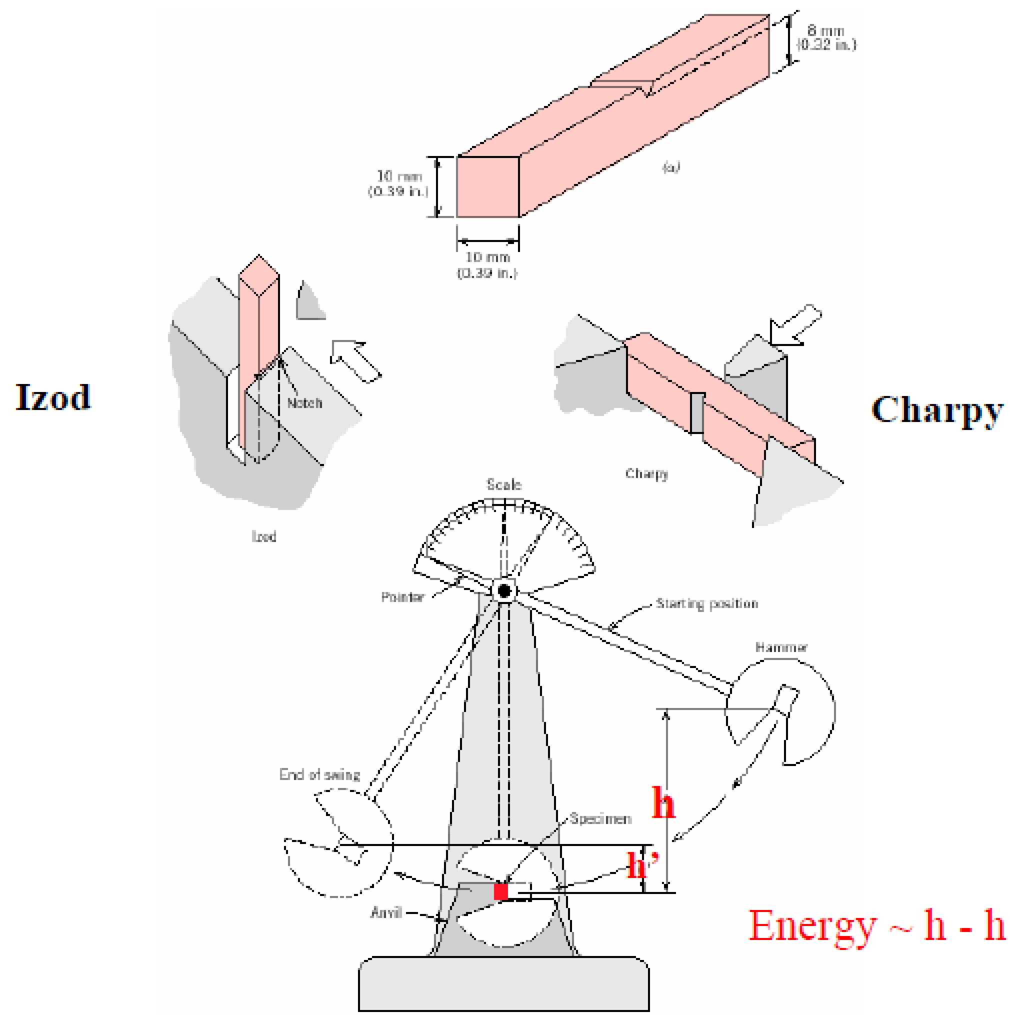
γ_s = specific surface energy

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)

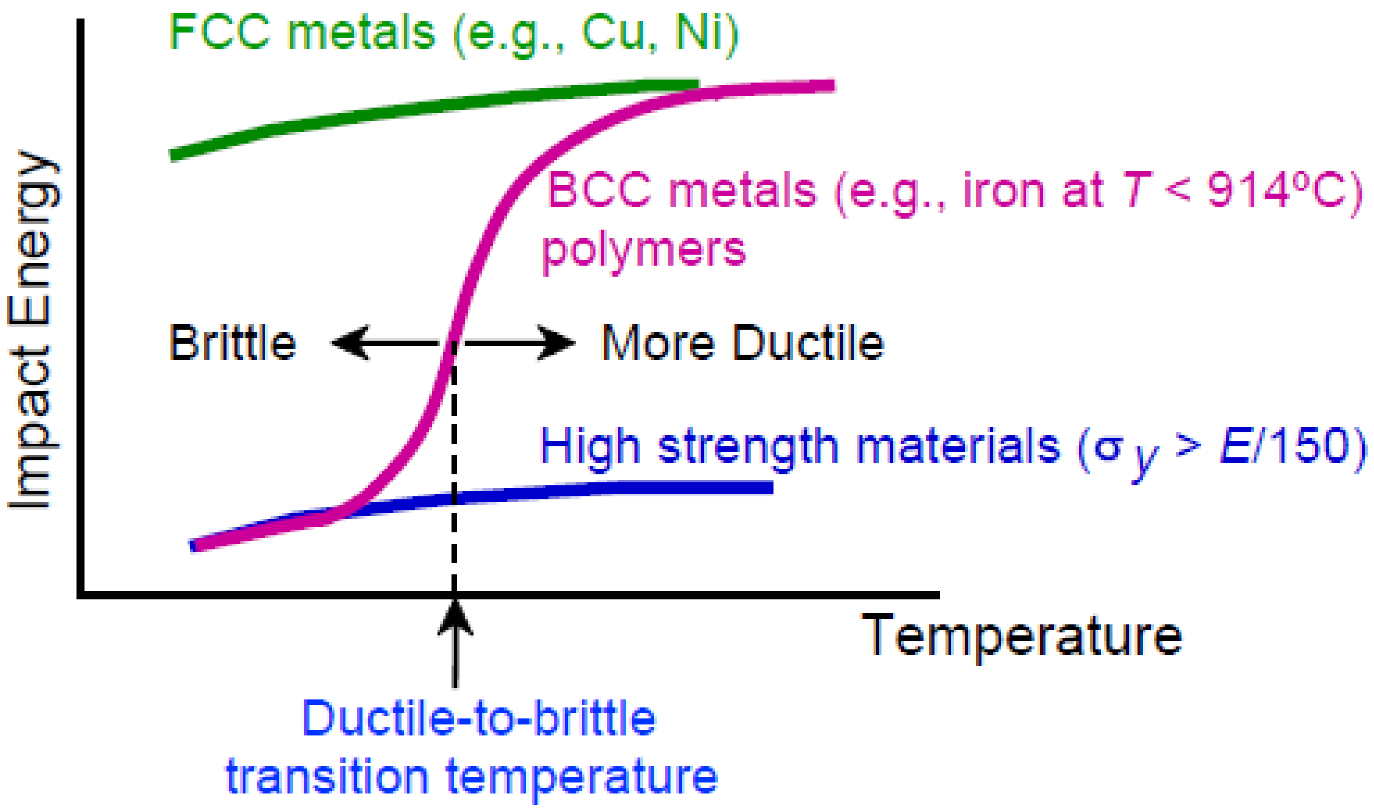
- Two standard tests, the **Charpy and Izod, measure the impact energy (the energy required to fracture a test piece** under an impact load), also called the notch toughness.



Ductile-to-brittle transition

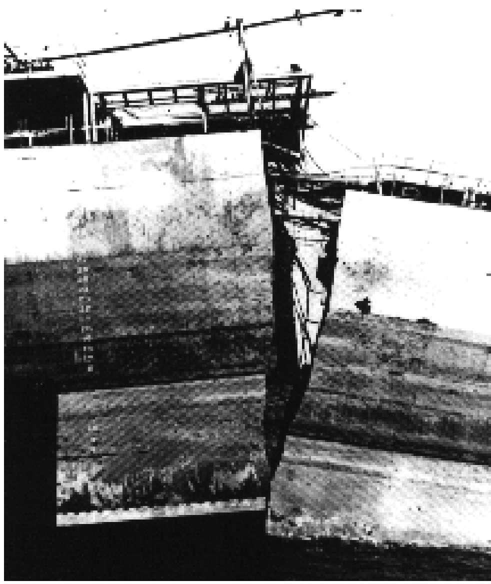
- As temperature decreases a ductile material can become brittle - ductile-to-brittle transition.
- Alloying usually increases the ductile-to-brittle transition temperature. FCC metals remain ductile down to very low temperatures. For ceramics, this type of transition occurs at much higher temperatures 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



Ductile-to-brittle transition

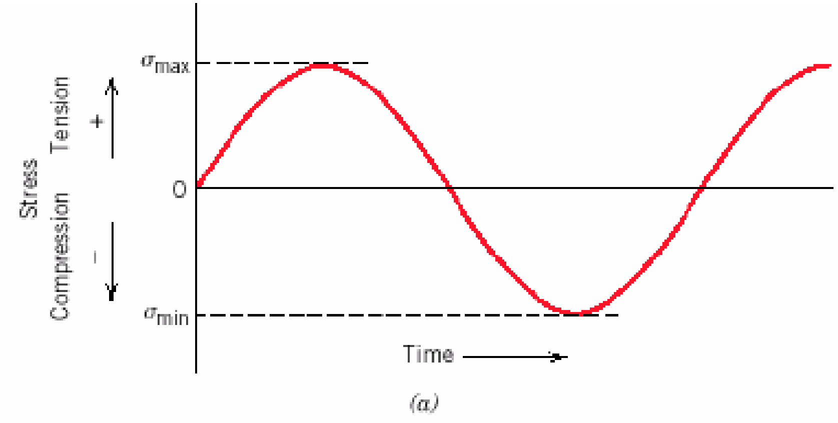
- Low temperatures can severely embrittle steels. The Liberty ships, produced in great numbers during the WWII were the first all-welded ships. A significant number of ships failed by catastrophic fracture. Fatigue cracks nucleated at the corners of square hatches and propagated rapidly by brittle fracture.



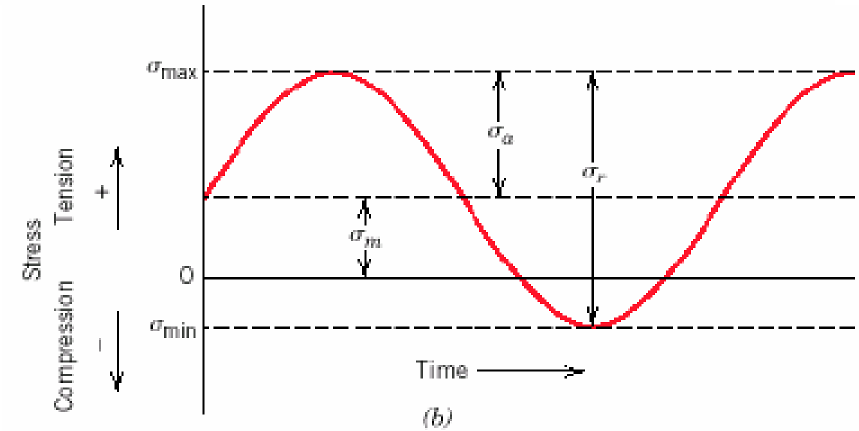
Fatigue
(Failure under fluctuating / cyclic stresses)

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

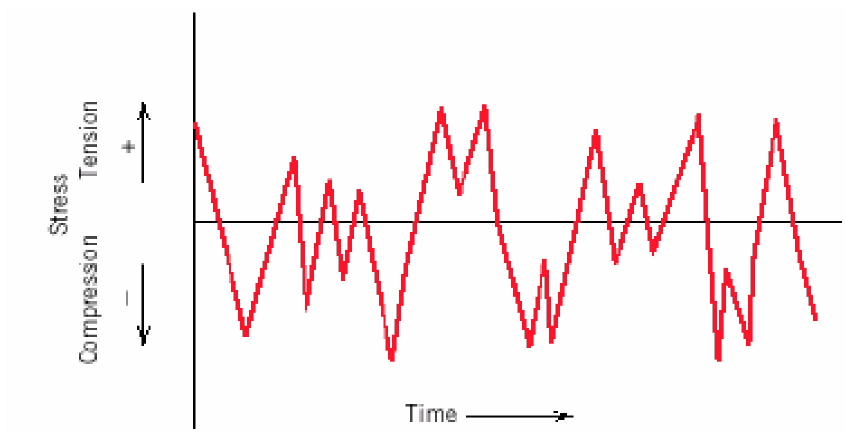
Fatigue: Cyclic Stresses (I)



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

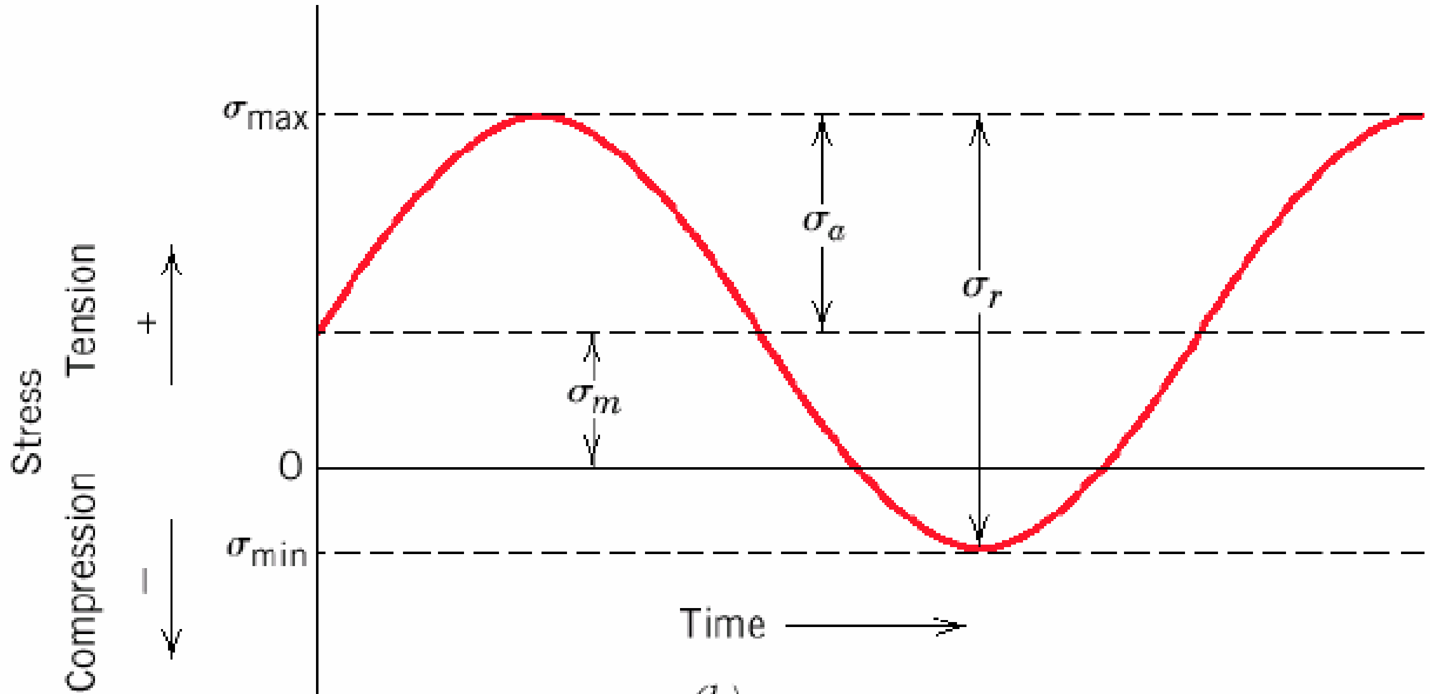
Mean stress:	$\sigma_m = (\sigma_{max} + \sigma_{min}) / 2$
Range of stress:	$\sigma_r = (\sigma_{max} - \sigma_{min})$
Stress amplitude:	$\sigma_a = \sigma_r/2 = (\sigma_{max} - \sigma_{min}) / 2$
Stress ratio:	$R = \sigma_{min} / \sigma_{max}$

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

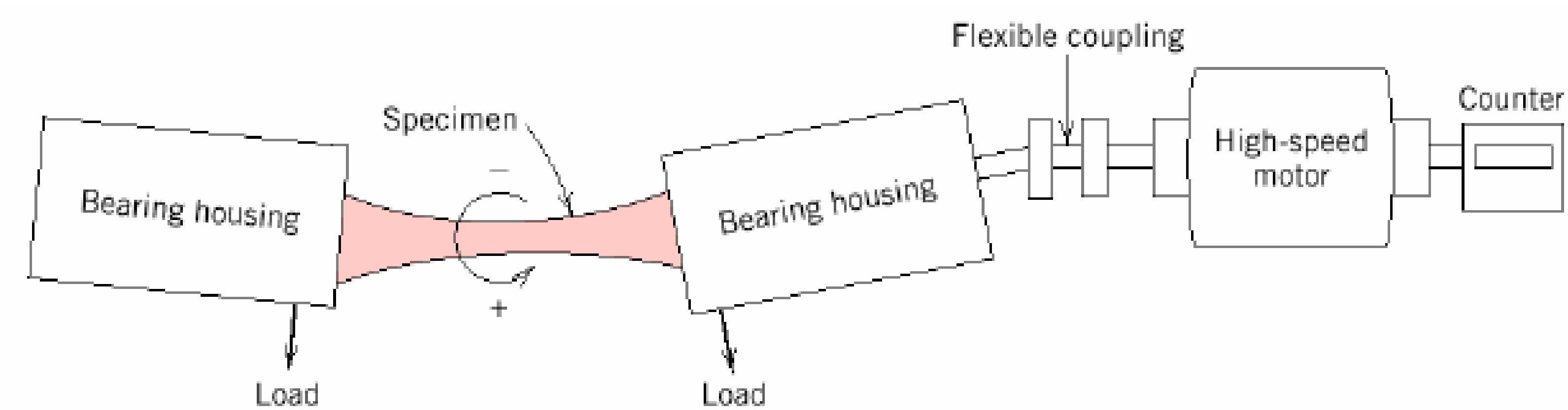


(b)

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:

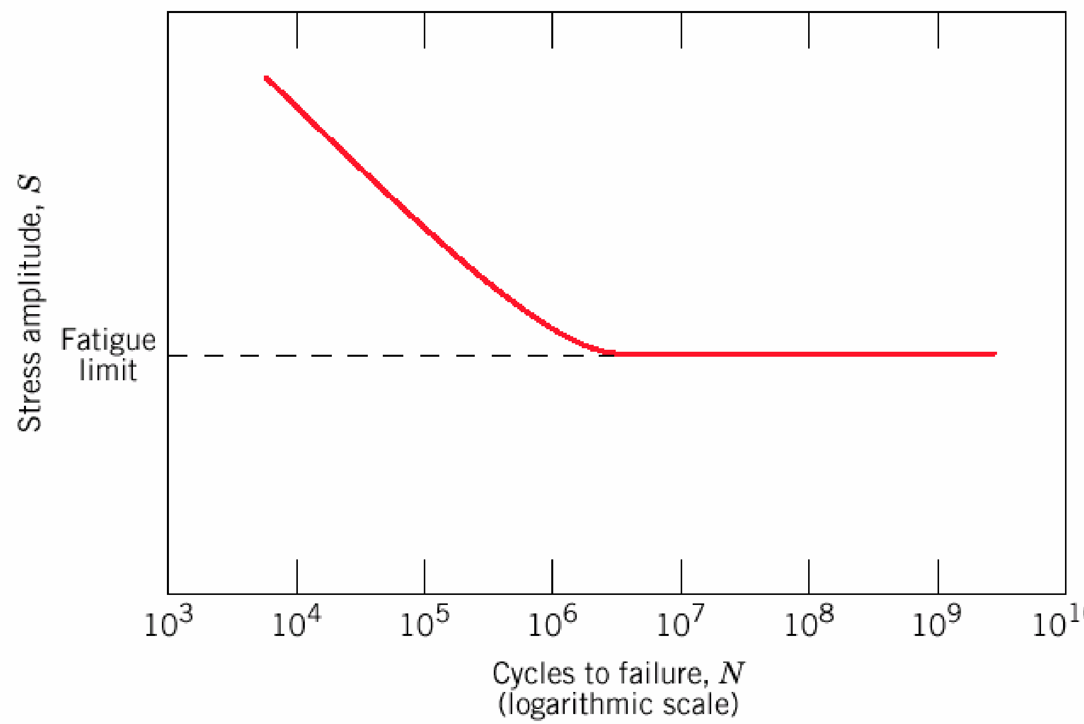


- Result is commonly plotted as S (stress) vs. N (number of cycles to failure)

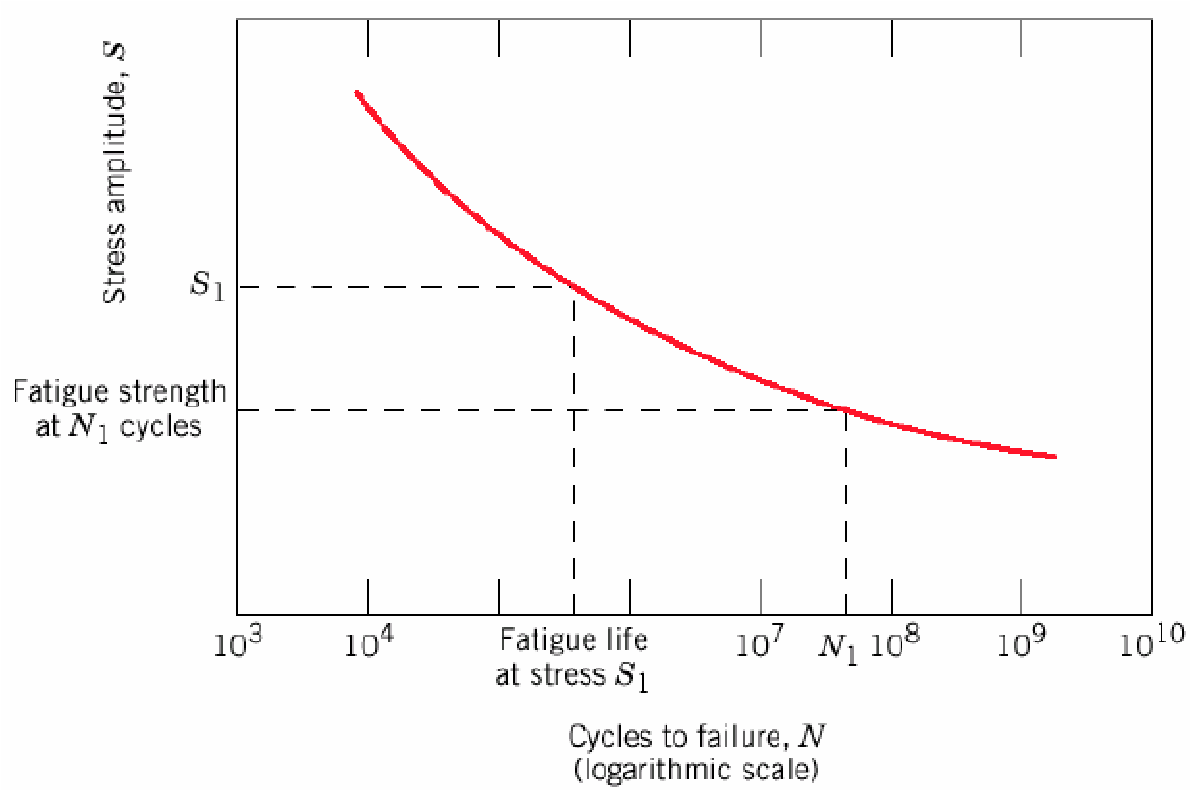
Fatigue: S—N curves (II)

- **Low cycle fatigue: high loads, plastic and elastic** deformation
- **High cycle fatigue: low loads, elastic deformation (N >** 10^5)

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:

$$N_f = N_i + N_p$$

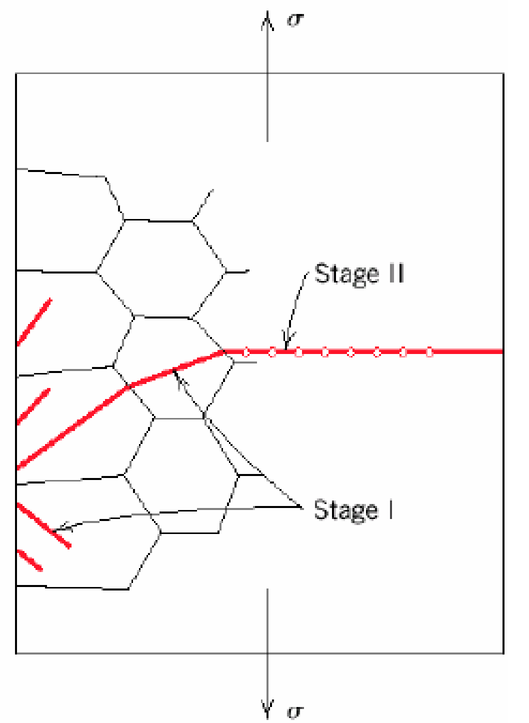
- $N_f = N_i + N_p$
- N_f : Number of cycles to failure
- N_i : Number of cycles for crack initiation
- N_p : Number of cycles for crack propagation
- High cycle fatigue (low loads): N_i is relatively high. With increasing stress level, N_i decreases and N_p dominates

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

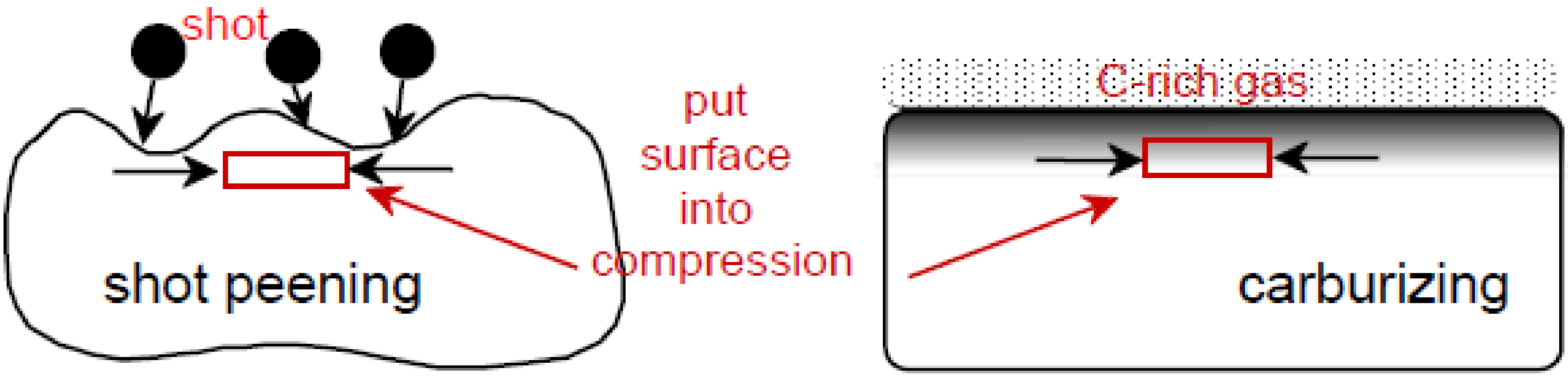
  ✓Stage II: faster propagation perpendicular to the applied stress. Crack grows by repetitive blunting and sharpening process at crack tip. **Rough fracture surface.**



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.


shot
shot peening
put
surface
into
compression
C-rich gas
carburizing

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.

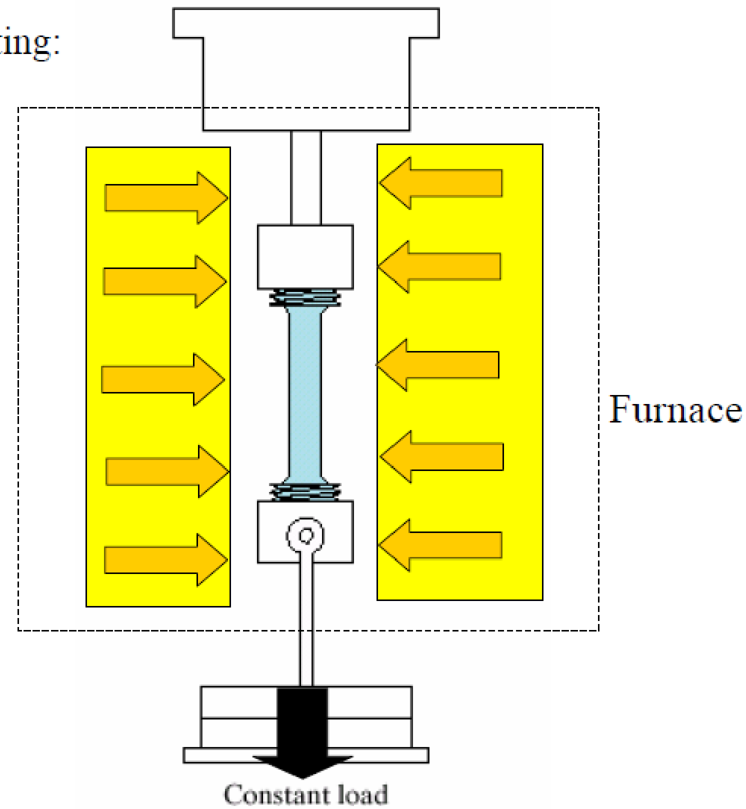
Solutions:

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

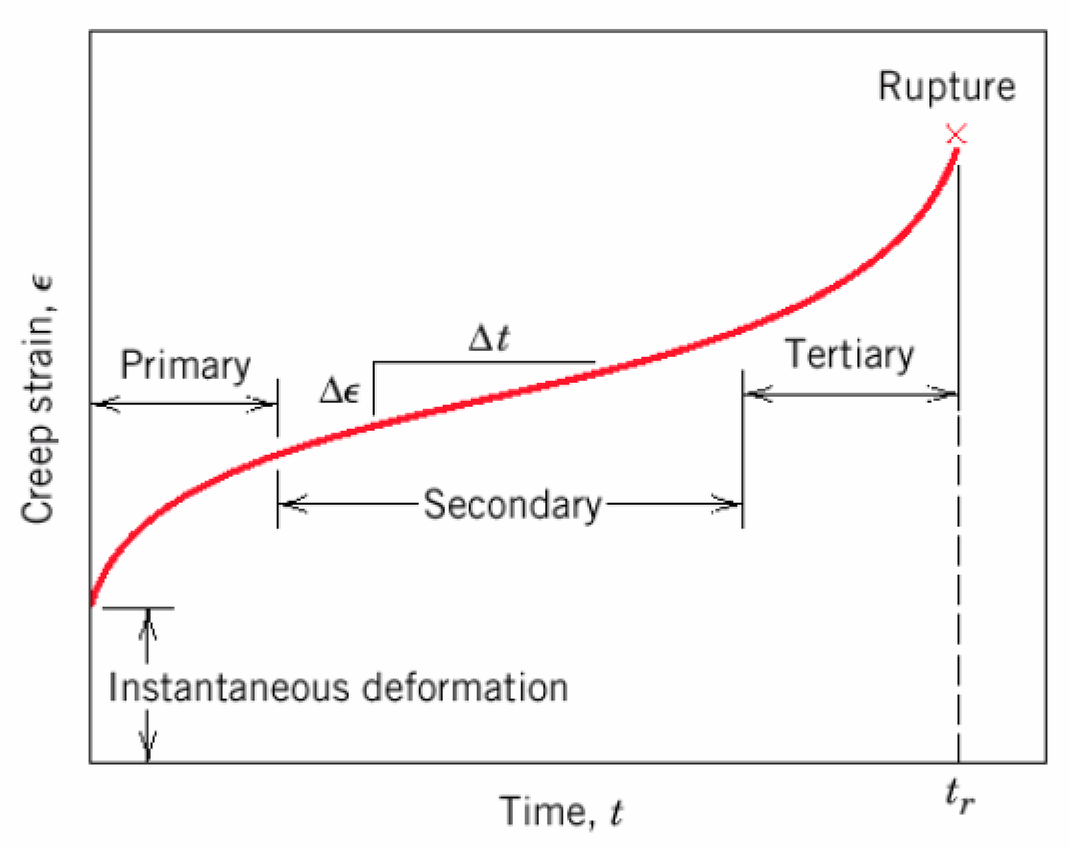
Creep

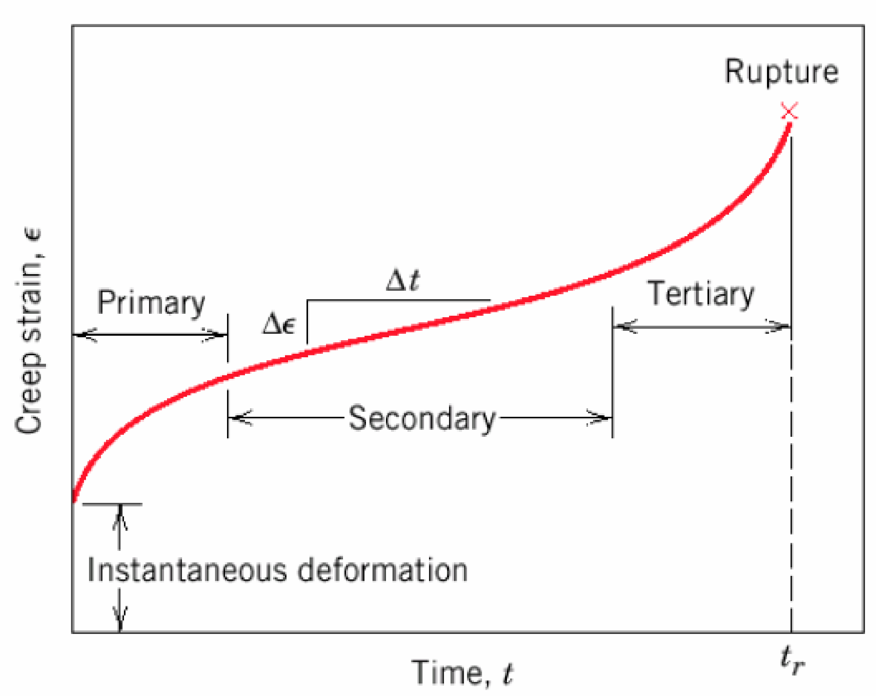
- Creep is a **time-dependent and permanent deformation** of materials when subjected to a constant load at a **high temperature (> 0.4 T_m). Examples: turbine blades, steam** generators.

Creep testing:



Stages of creep





1. Instantaneous deformation, mainly elastic.

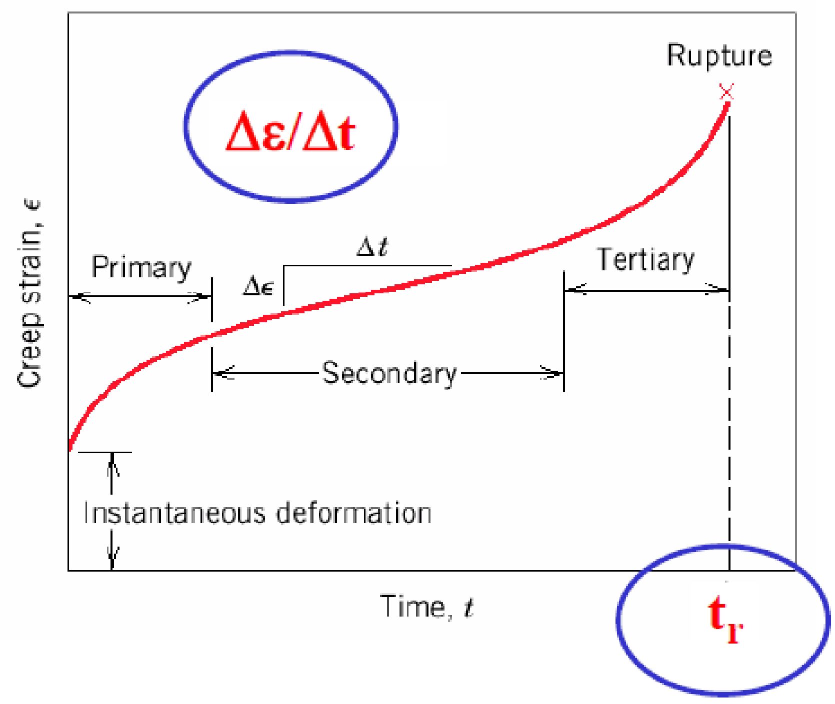
2. Primary/transient creep. Slope of strain vs. time decreases with time: work-hardening

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

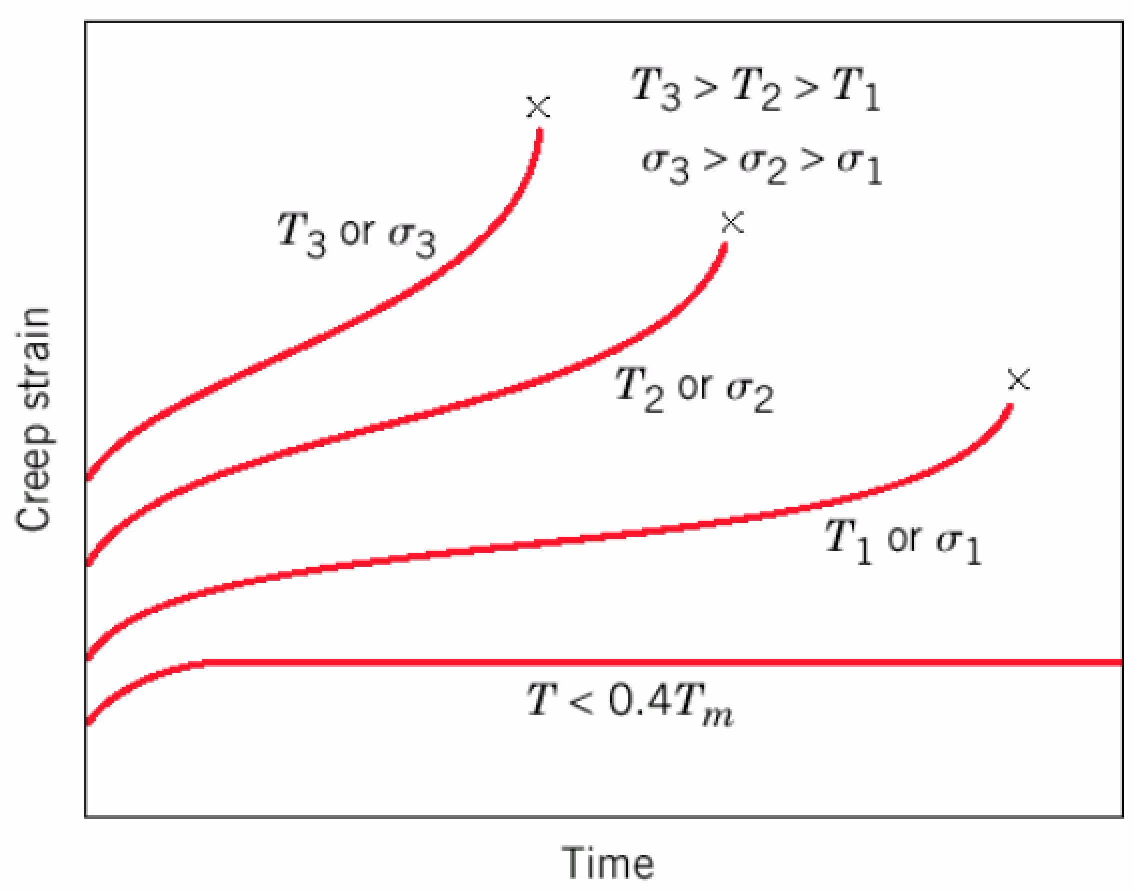
- The stage of secondary/steady-state creep is of longest duration and the **steady-state creep rate** $\dot{\varepsilon}_s = \Delta\varepsilon / \Delta t$ is the most important parameter of the creep behavior in long-life applications.
- Another parameter, especially important in short-life creep situations,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

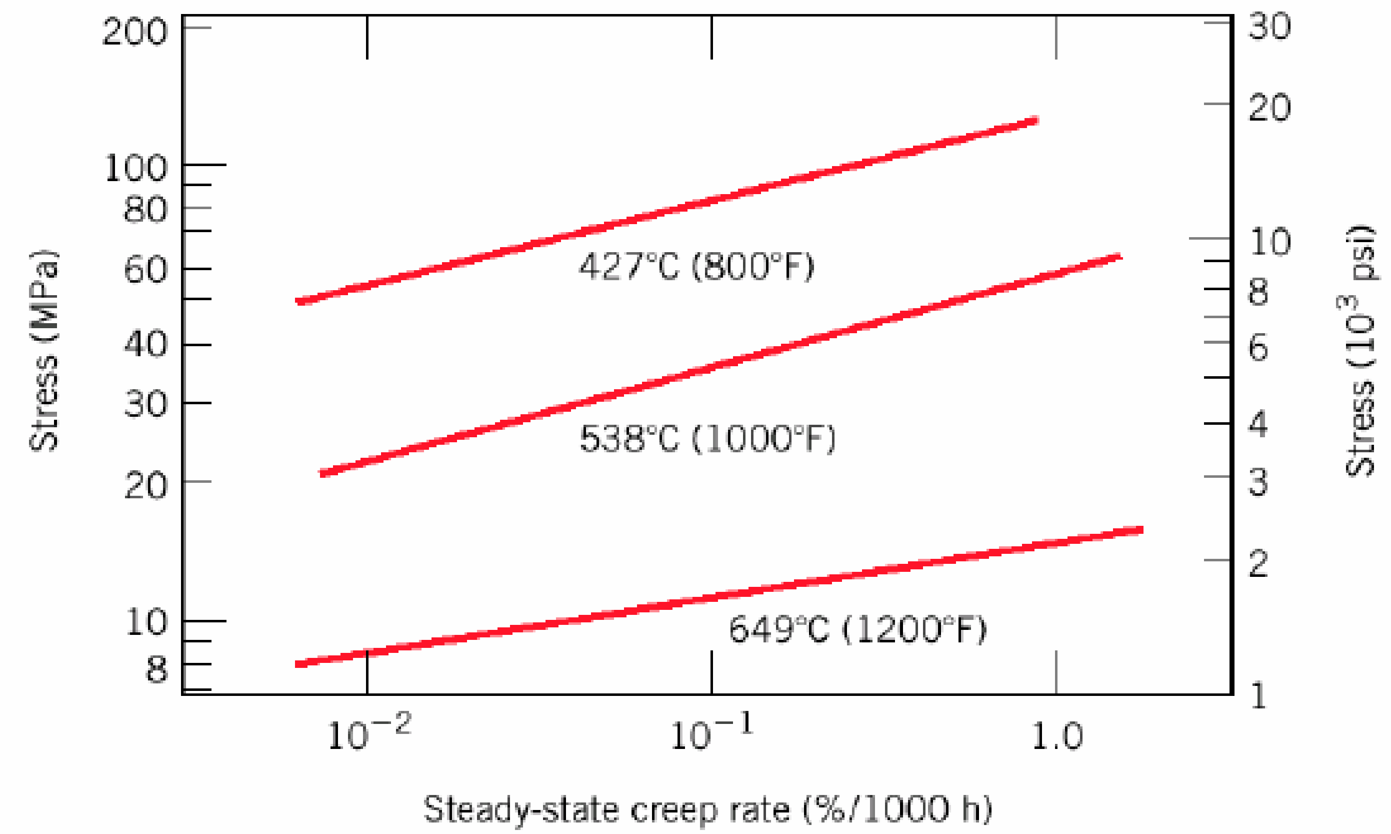


Creep: stress and temperature effects

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

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

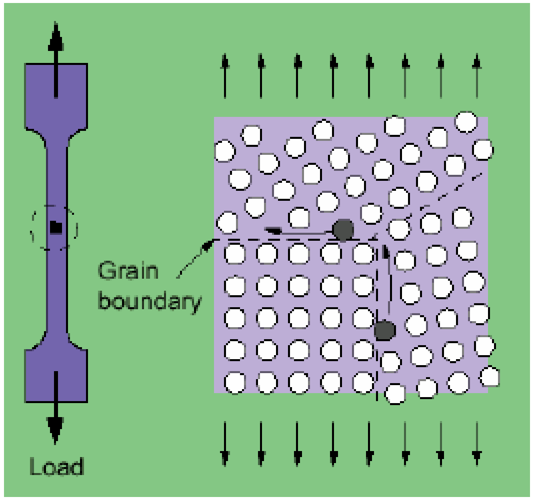
- where Q_c is the activation energy for creep, K_2 and n are material constants.
- (Remember the Arrhenius dependence on temperature for thermally activated processes that we discussed for diffusion)



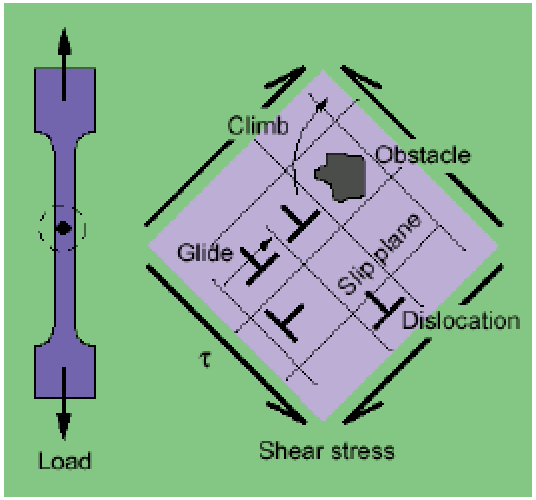
200
100
80
60
40
30
20
10
8
Stress (MPa)
30
20
10
8
6
4
3
2
1
Stress (10^3 psi)
427°C (800°F)
538°C (1000°F)
649°C (1200°F)
10^{-2}
10^{-1}
1.0
Steady-state creep rate (%/1000 h)

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)

- **<u>Summary</u>**

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