Chapter 6
Mechanical Failure

The University of Jordan
Chemical Engineering Department
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Prof. Yousef Mubarak

Outline

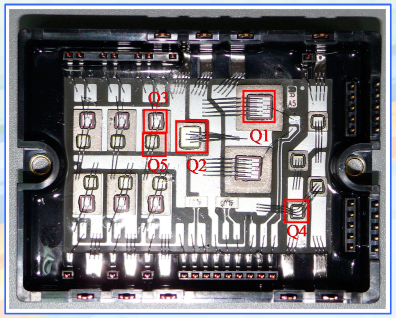
- How do Materials Break?

  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

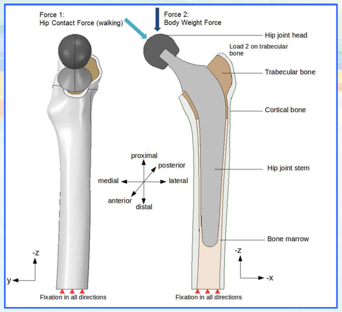
ISSUES TO ADDRESS...

- *How do cracks that lead to failure form?*
- *How is fracture resistance quantified? How do the fracture resistances of the different material classes compare?*
- *How do we estimate the stress to fracture?*
- *How do loading rate, loading history, and temperature affect the failure behavior of materials?*

Ship-cyclic loading from waves



Computer chip-cyclic thermal loading



Hip implant-cyclic loading from walking

Why study failure?

- Design of a component or structure: Minimize failure possibility
- It can be accomplished by understanding the mechanics of failure modes and applying appropriate design principles.
- Failure cost
  1. Human life
  2. Economic loss
  3. Unavailability of service
- Failure causes
  1. Improper material selection
  2. Inadequate design
  3. Processing
- Regular inspection, repair and replacement critical to safe design.

Fracture

- Fracture is the separation of a body into two or more pieces in response to an imposed stress.
- Steps in fracture:
  1. Crack formation
  2. Crack propagation
- Depending on the ability of material to undergo plastic deformation before the fracture two modes can be defined:
  1. Ductile fracture
  2. Brittle fracture

Fracture Modes

Ductile fracture

- Most metals (not too cold) exhibit ductile fracture.
- Extensive plastic deformation ahead of crack.
- Crack is "stable": resists further extension unless applied stress in increased.

Brittle fracture

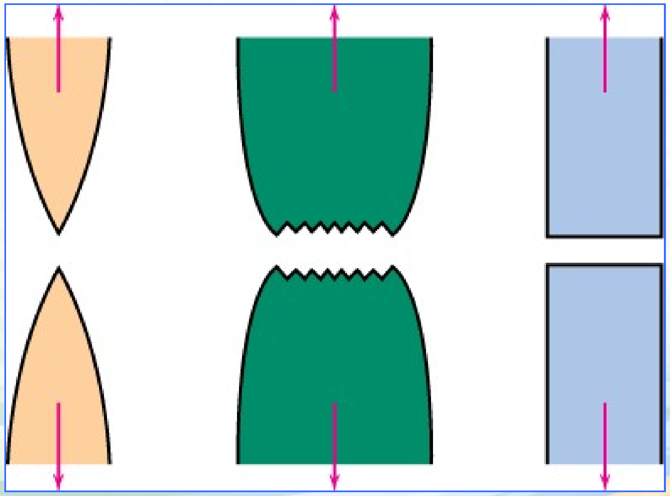
- Ceramics, ice, cold metals exhibit brittle fracture.
- Relatively little plastic deformation
- Crack is "unstable": propagates rapidly without increase in applied stress.
- Catastrophic

- Ductile fracture is preferred in most applications.

Ductile vs Brittle Failure

- **Classification:**

Fracture behavior:	Very Ductile	Moderately Ductile	Brittle



%AR or %EL	Large	Moderate	Small

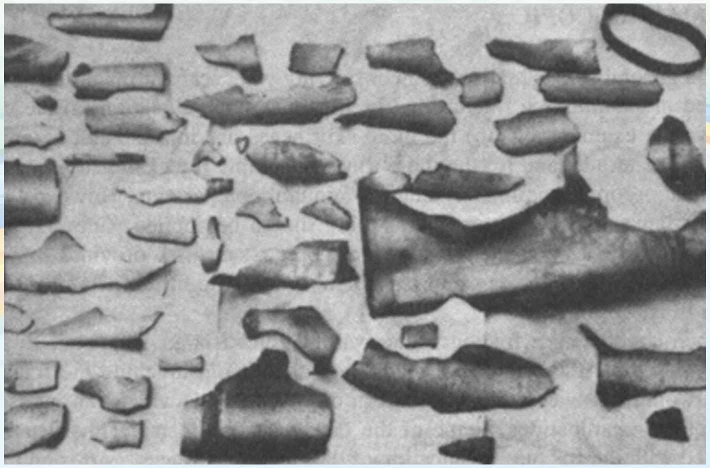
- Very ductile, soft metals (Pb, Au) at room temperature, other metals, polymers, glasses at high temperature.
- Moderately ductile fracture, typical for ductile metals.
- Brittle fracture, cold metals, ceramics

Ductile fracture is usually more desirable than brittle fracture!	Ductile Warning before fracture	Brittle No warning

Example: Pipe Failures

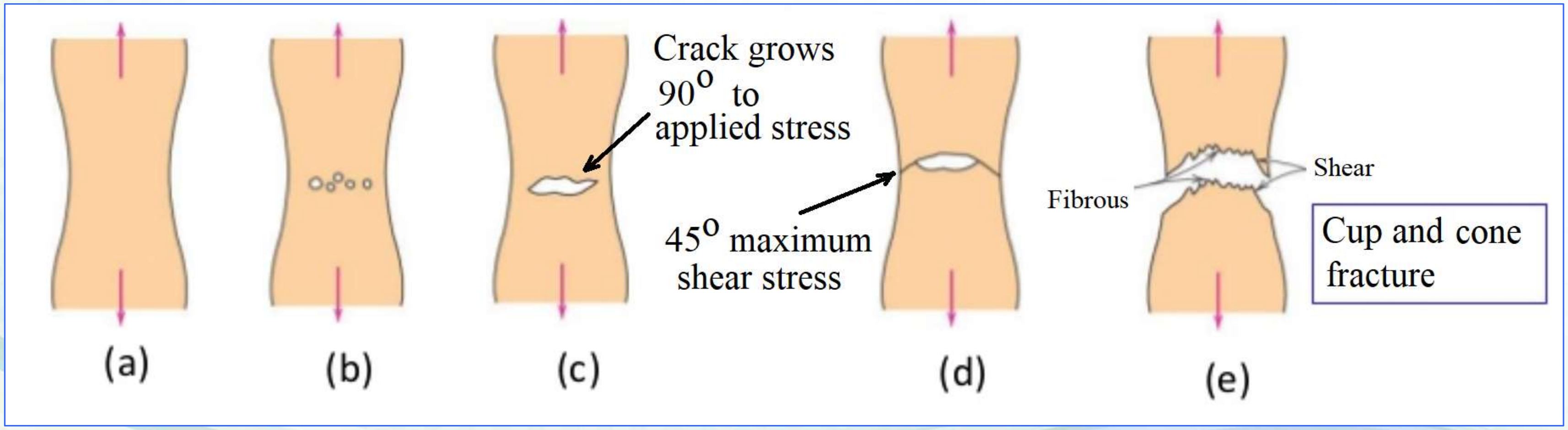
- Ductile failure:
  - One piece
  - Large deformation

- Brittle failure:
  - Many pieces
  - Small deformations



Ductile fracture

Failure stages:



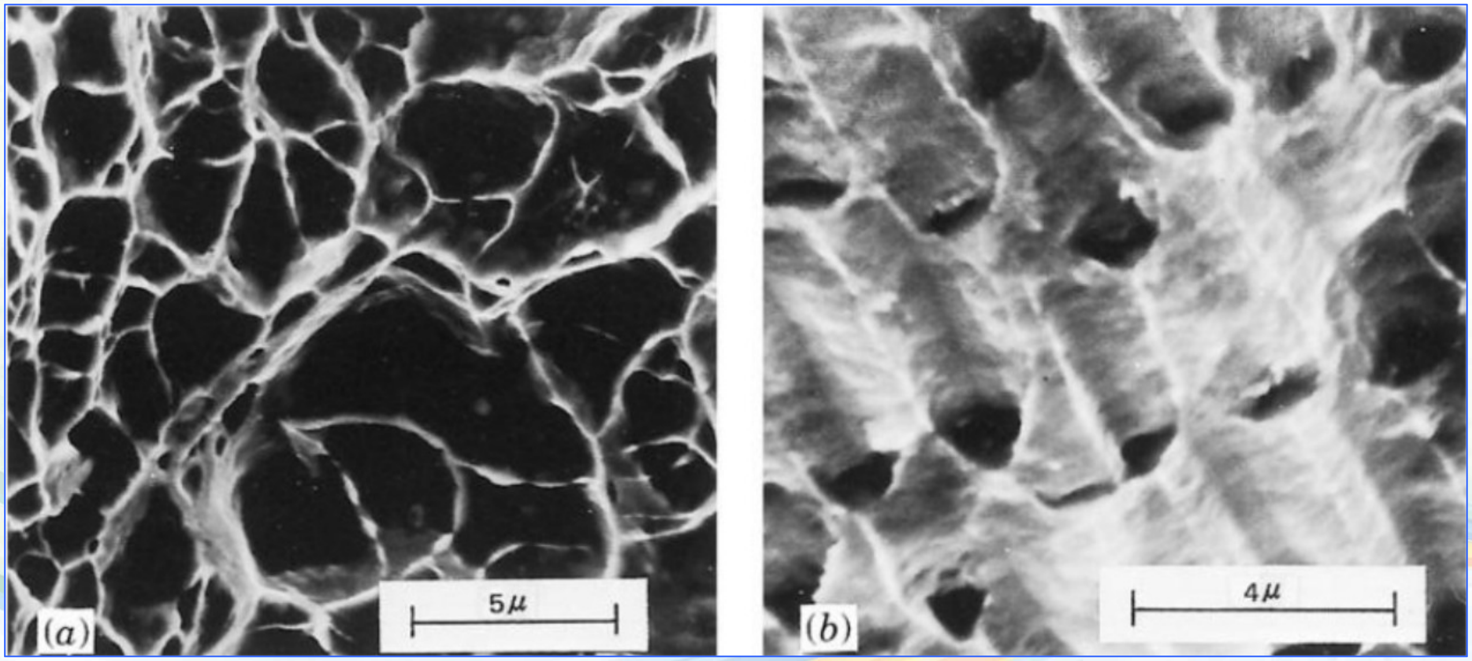
(a) Necking
(b) Formation of microvoids
(c) Coalescence of microvoids to form a crack
(d) Crack propagation by shear deformation
(e) Fracture

Moderately Ductile vs. Brittle Failure

Cup-and-cone fracture in ductile Al

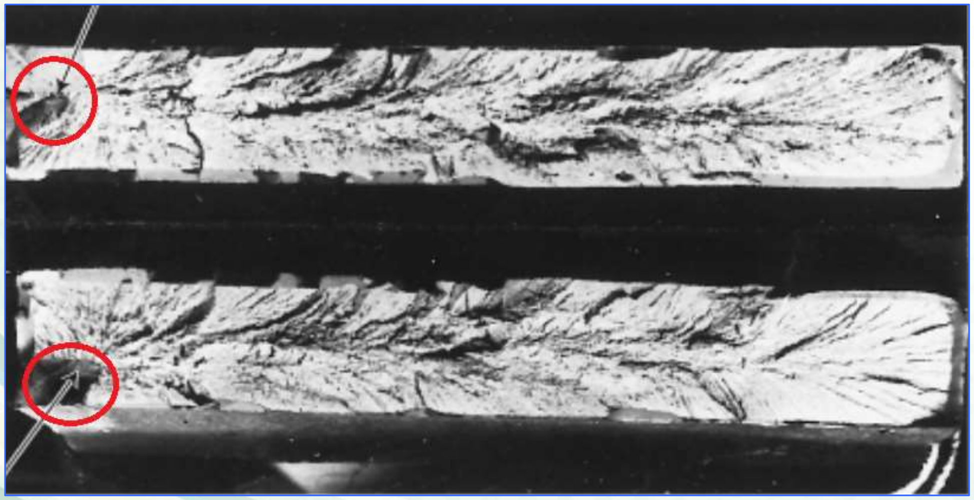
Brittle fracture in mild steel

Ductile fracture

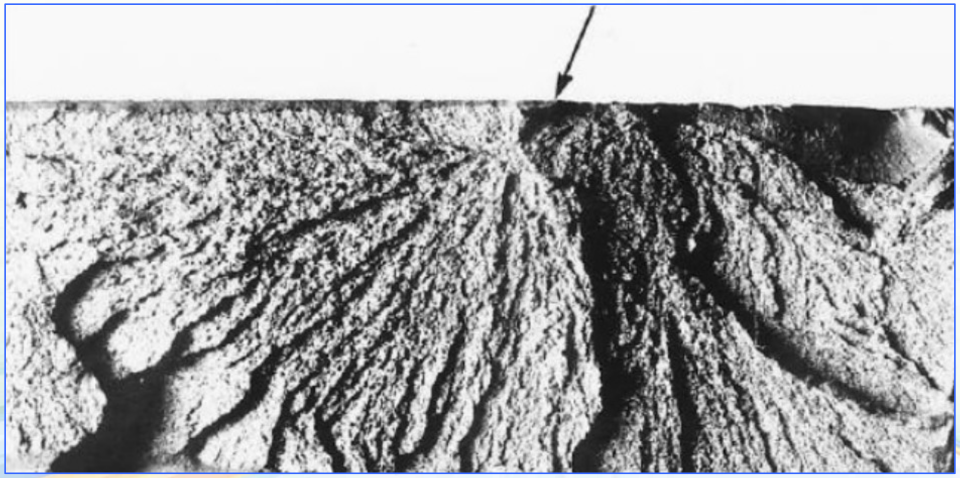


(a) SEM image showing spherical dimples resulting from a uniaxial tensile load representing microvoids. (b) SEM image of parabolic dimples from shear loading.

Brittle Failure

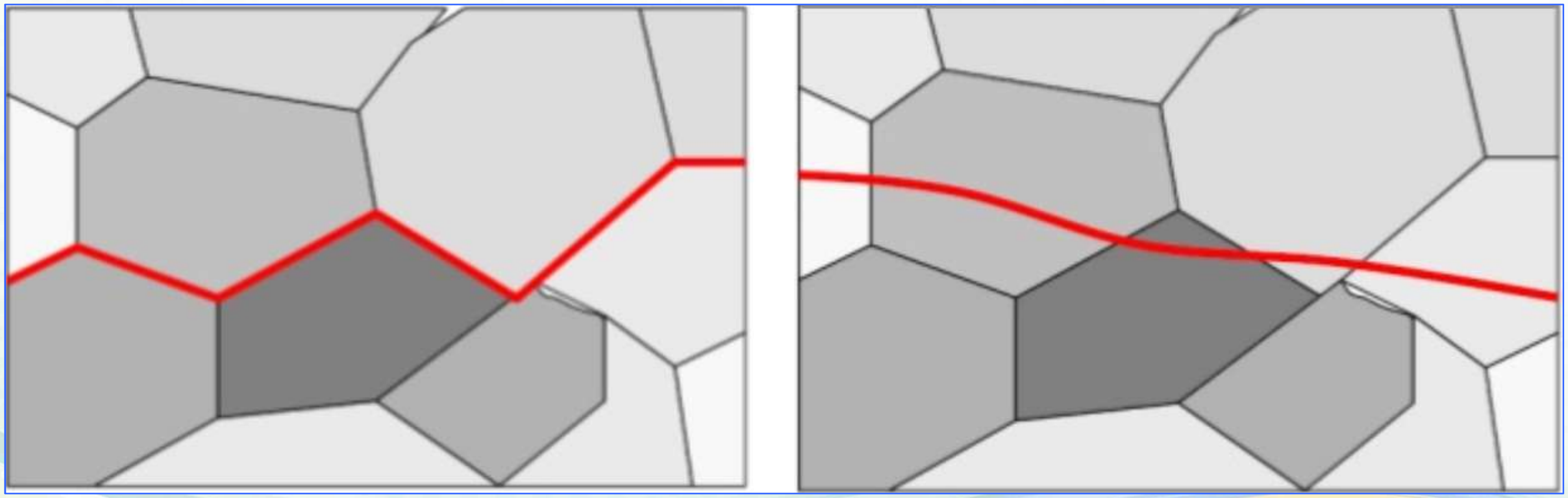


Red circles with arrows indicate point at which failure originated



Lines or ridges that radiate from the origin of the crack in a fanlike pattern

Brittle Fracture Surfaces



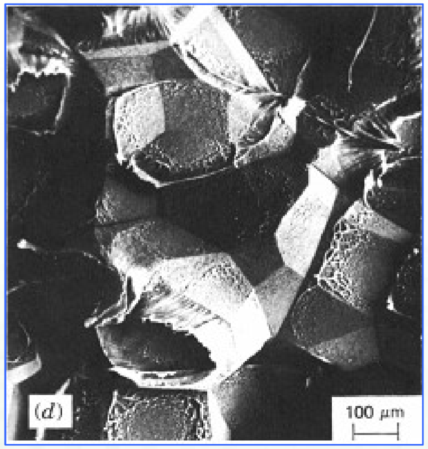
Intergranular fracture:
Fracture crack propagation is along grain boundaries (grain boundaries are weakened or embrittled by impurities segregation etc.)

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

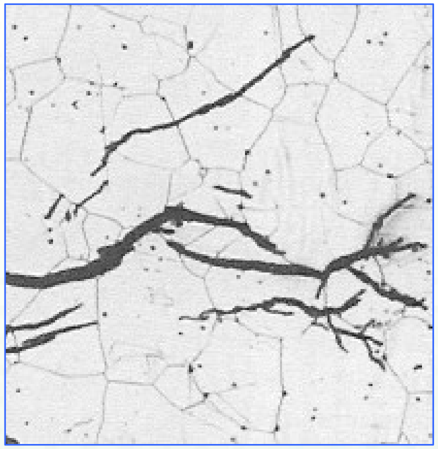
Brittle Fracture Surfaces

Intergranular (between grains)

304 S. Steel (metal)

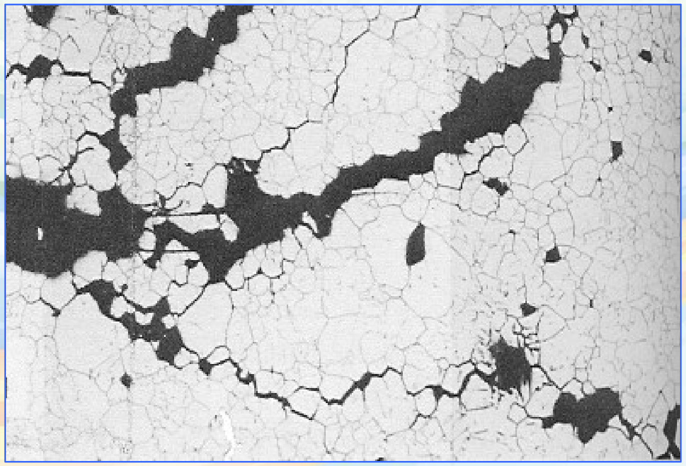


Transgranular (through grains)



S. Steel (metal)

Polypropylene (polymer)



Al Oxide (ceramic)

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).

Fracture Mechanics

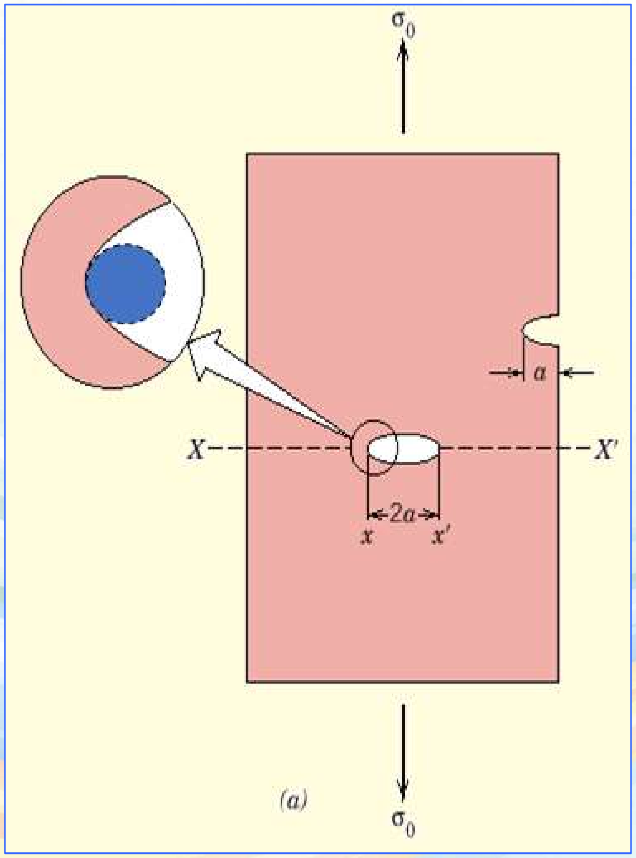
Studies the relationships between:

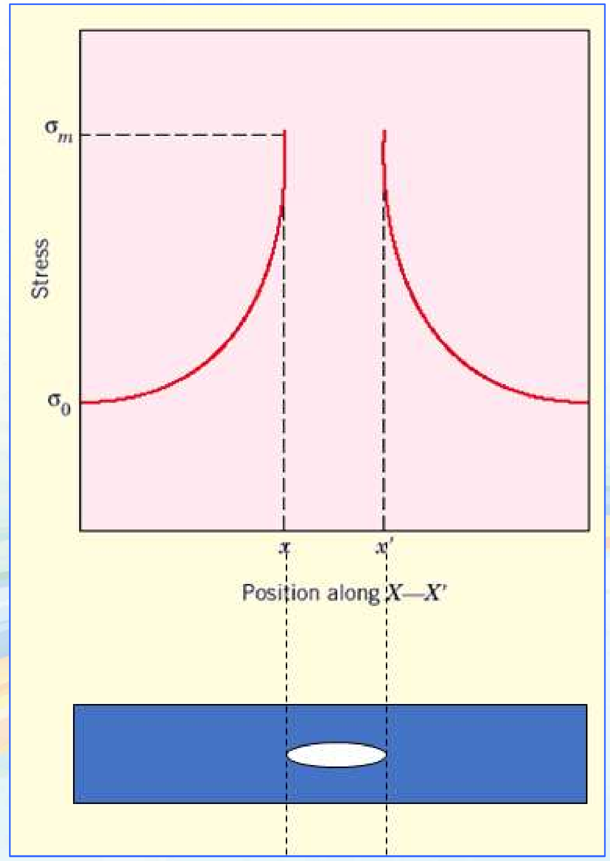
1. Material properties
2. Stress level
3. Crack producing flaws
4. Crack propagation mechanisms

Stress Concentration

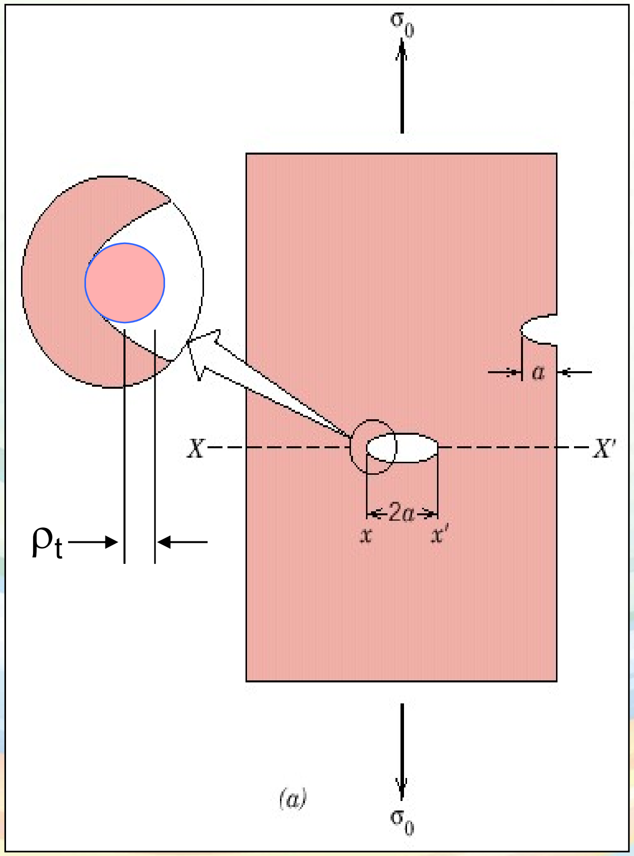
- Measured fracture strength is much lower than predicted by calculations based on atomic bond energies. This discrepancy is explained by the presence of flaws or cracks in the materials.
- The flaws act as stress concentrators or stress raisers, amplifying the stress at a given point.
- The magnitude of amplification depends on crack geometry and orientation

Concentration of Stress at Crack Tip





Flaws are Stress Concentrators



- If the crack is similar to an elliptical hole through plate, and is oriented perpendicular to applied stress, the maximum stress, at crack tip

$$\boldsymbol{\sigma_m = 2\sigma_o\left(\frac{a}{\rho_t}\right)^{1/2} = K_t\sigma_o}$$

where

ρ_t = radius of curvature

σ_o = applied stress

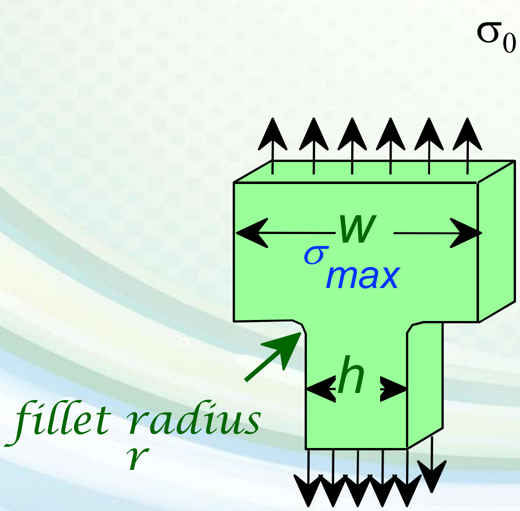
σ_m = stress at crack tip

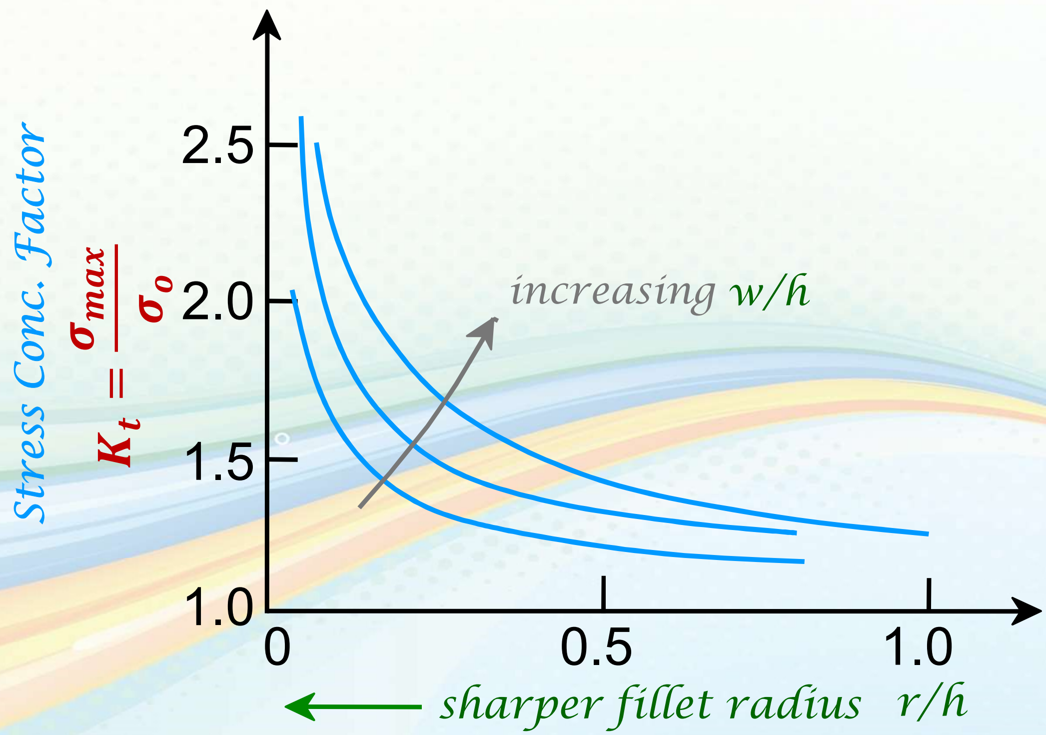
a = length of surface crack or ½ length of internal crack

$\mathcal{K}_t$ = stress concentration factor

Engineering Fracture Design

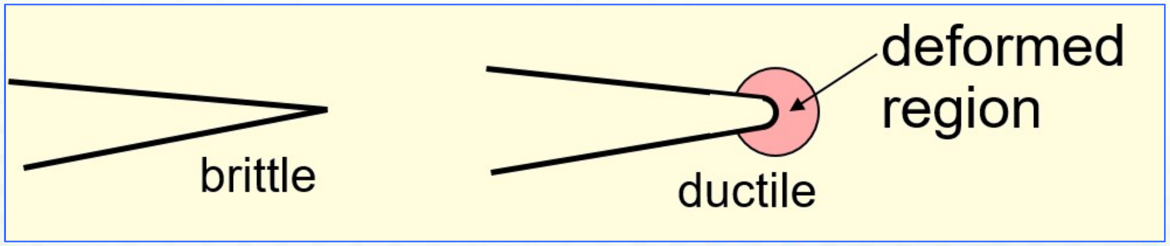
- Avoid sharp corners





Crack Propagation

- Cracks having sharp tips propagate easier than cracks having blunt tips
- A plastic material deforms at a crack tip, which "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

Criterion for Crack Propagation

- Crack propagates if crack-tip stress (σ_m) exceeds a critical stress (σ_c)

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

- When the tensile stress at the tip of crack exceeds the critical stress value the crack propagates and results in fracture.

where

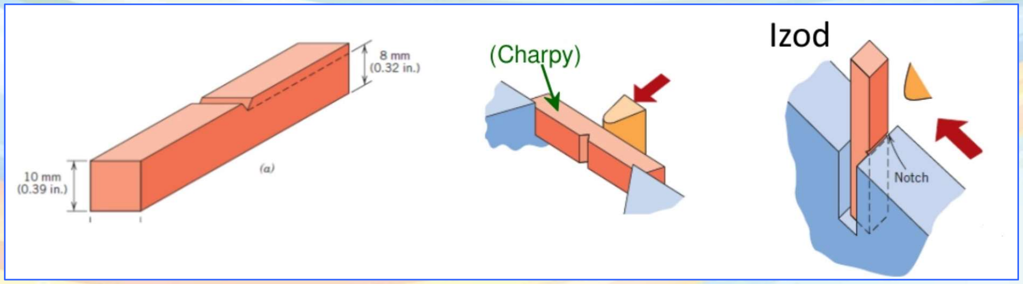
  - E = modulus of elasticity
  - γ_s = specific surface energy
  - a = one half length of internal crack

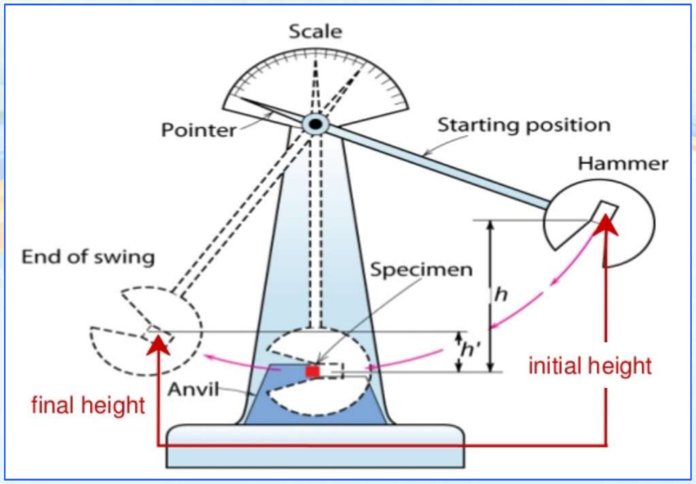
- For ductile materials ⟶ replace γ_s with $\gamma_s + \gamma_p$

  where γ_p is plastic deformation energy

Impact Fracture Testing

- *Impact tests are used in studying the toughness of material. A material's toughness is a factor of its ability to absorb energy during plastic deformation.*
- *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*





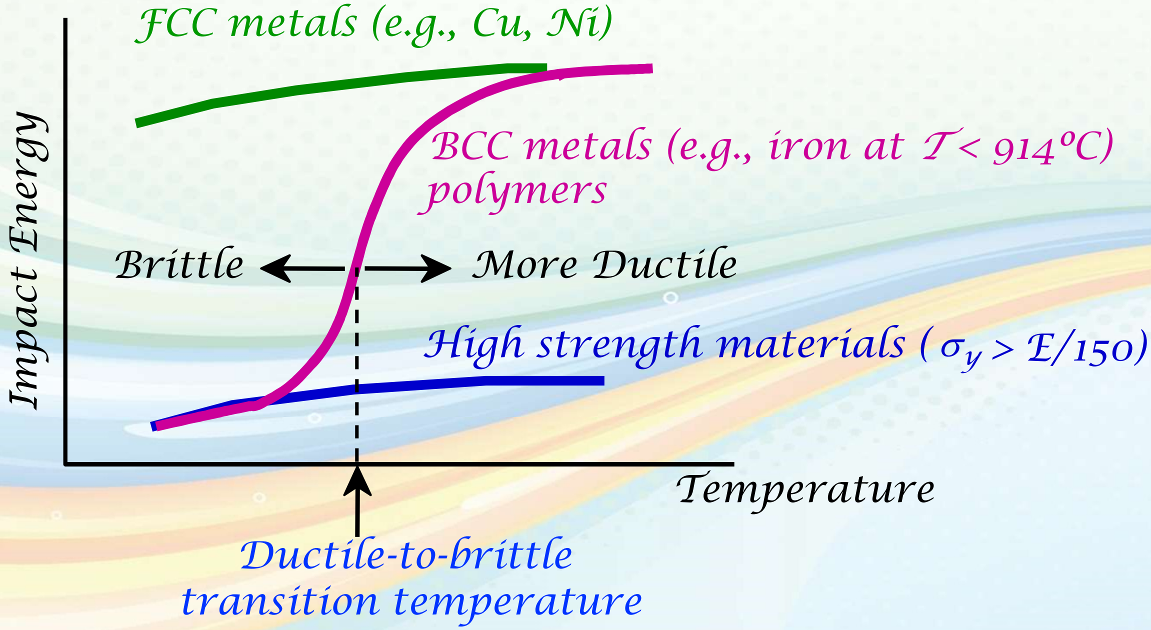
Ductile-to-brittle transition

- 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.

Influence of Temperature on Impact Energy

- Impact energy increases with increasing temperature to a point at which further increases in temperature do not cause a significant increase in impact energy

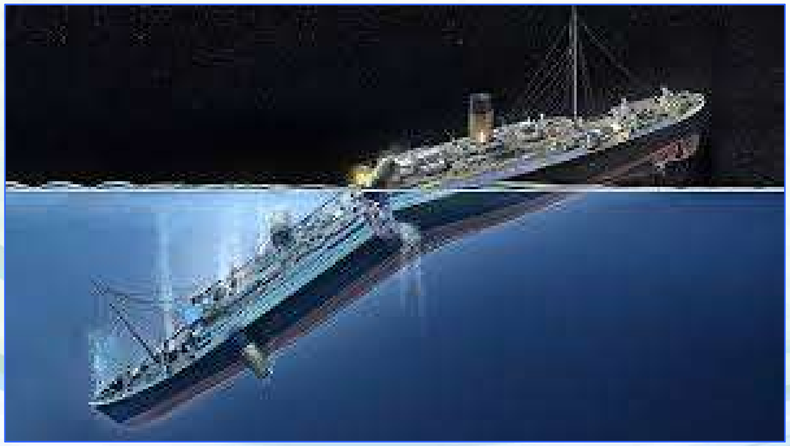
Ductile-to-Brittle Transition Temperature (DBTT)...



Design Strategy:

Stay Above The DBTT!

The Titanic



Liberty ships

- *Problem:* Steels were used having DBTT's just below room temperature.

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

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

1- Mean stress: $$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$$

2- Range of stress: $$\sigma_r = \Delta\sigma = \sigma_{max} - \sigma_{min}$$

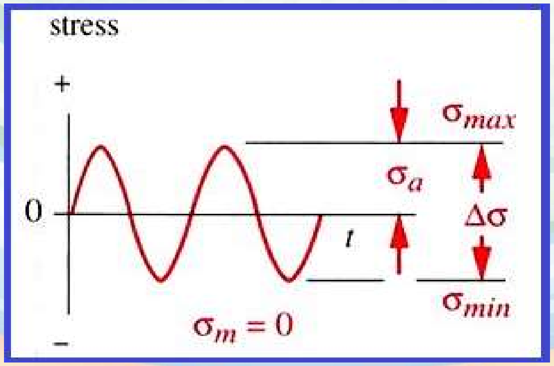
3- Stress amplitude: $$\sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{max} - \sigma_{min}}{2}$$

4- Stress ratio: $$R = \frac{\sigma_{min}}{\sigma_{max}}$$

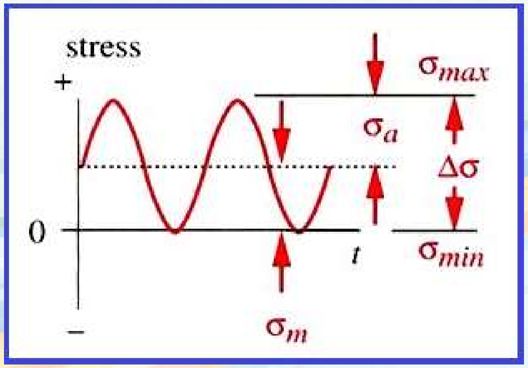
- Remember the convention that tensile stresses are positive, compressive stresses are negative.

Fatigue: Cyclic Stresses II

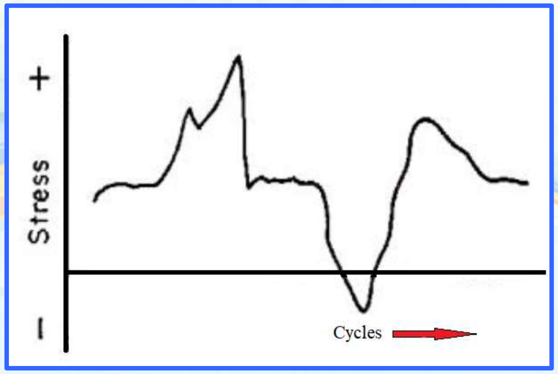
1- Reversed stress cycle: the stress alternates from a maximum tensile stress to a maximum compressive stress of equal magnitude



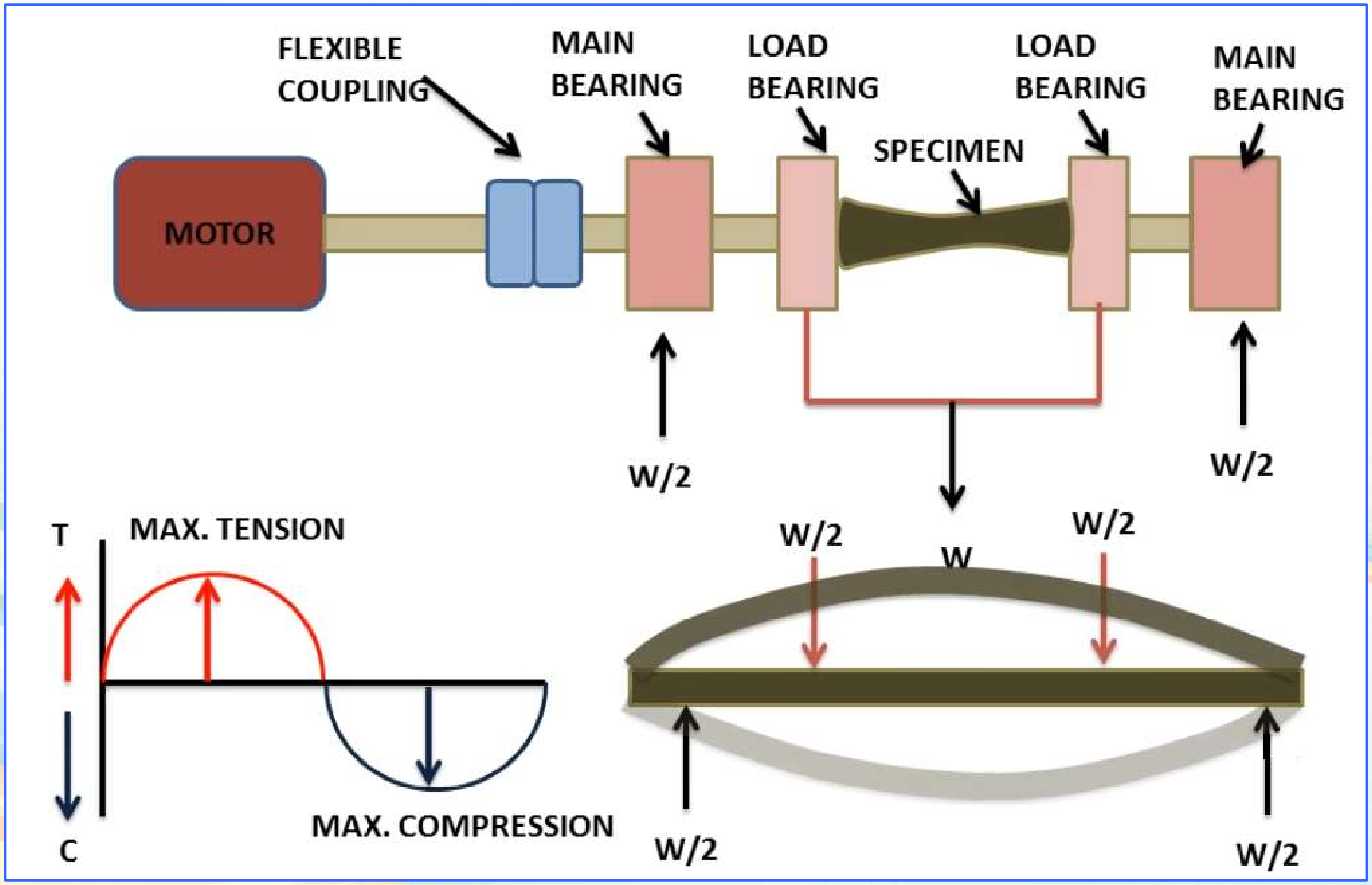
2- Repeated stress cycle: maximum and minimum stresses are asymmetrical relative to the zero stress level



3- Random stress fluctuation



- Alternating stress $$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}$$
- Mean stress $$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$$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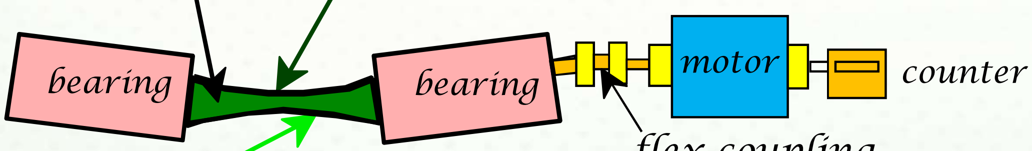
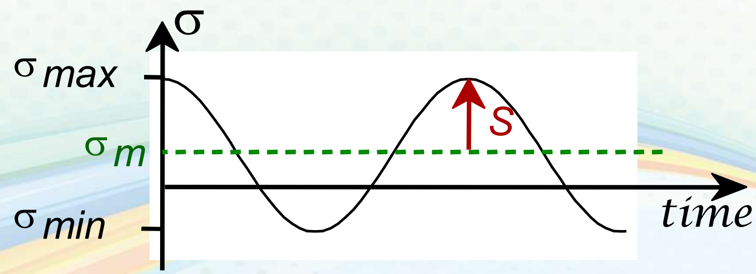
COUPLING
MAIN
BEARING
LOAD
BEARING
SPECIMEN
LOAD
BEARING
MAIN
BEARING
MOTOR
W/2
W/2
T
MAX. TENSION
W/2
W
W/2
C
MAX. COMPRESSION
W/2
W/2

Fatigue

- **Fatigue** = failure under applied cyclic stress.



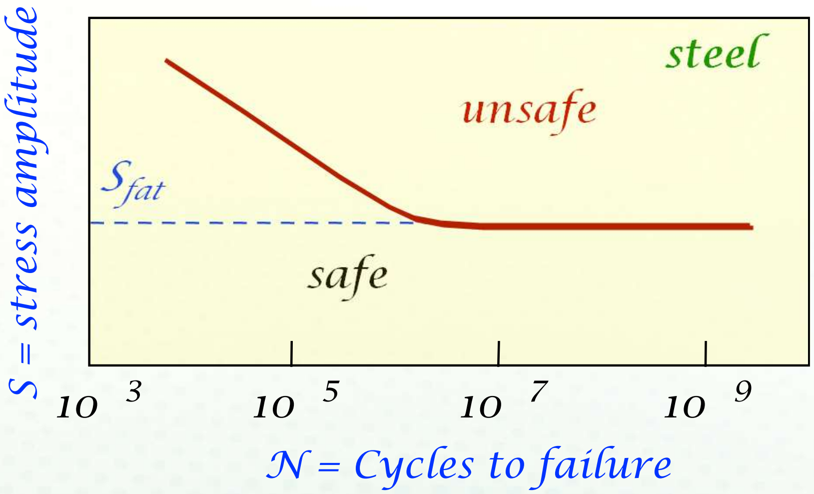
- Stress varies with time.
    - Key parameters are S, σ_m, and cycling frequency



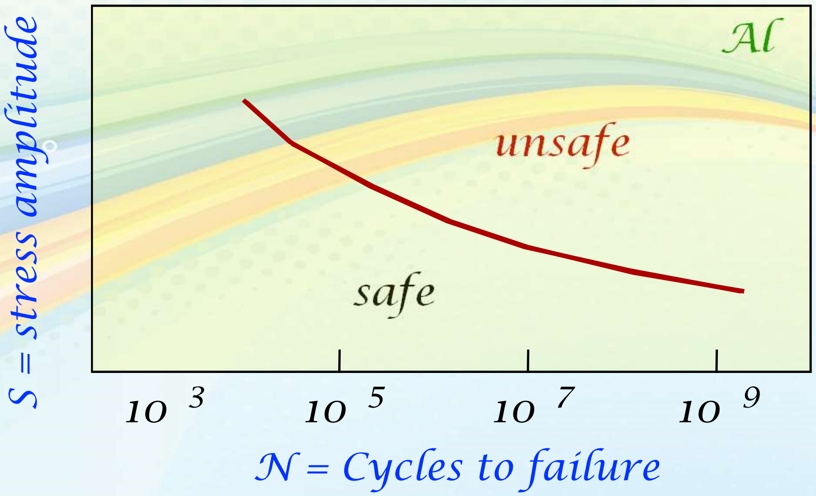
- Key points: Fatigue...
    - Can cause part failure, even though $\sigma_{max} < \sigma_c$.
    - Responsible for ~ 90% of mechanical engineering failures.

Types of Fatigue Behavior

- Fatigue limit, S_{fat}:
  - no fatigue if $S < S_{fat}$



- For some materials, there is no fatigue limit!



Rate of Fatigue Crack Growth

- Crack grows incrementally

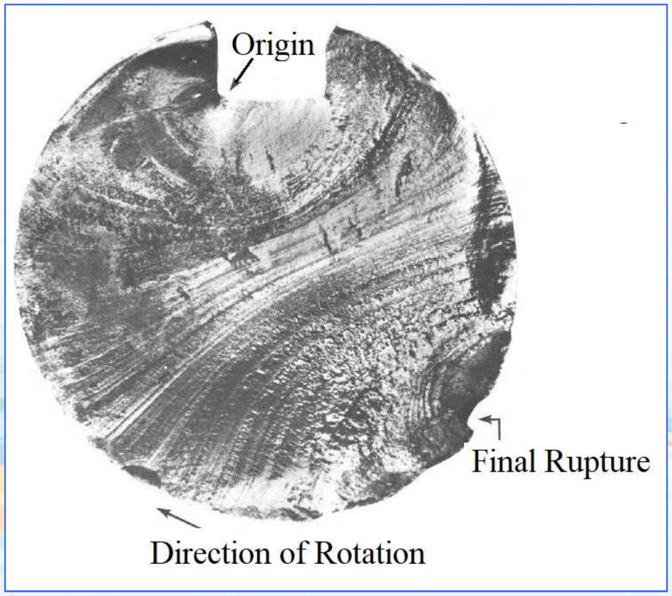
$$\frac{da}{dN} = (\Delta K)^m$$

m: typ. 1 to 6

$\Delta K \sim (\Delta\sigma)\sqrt{a}$

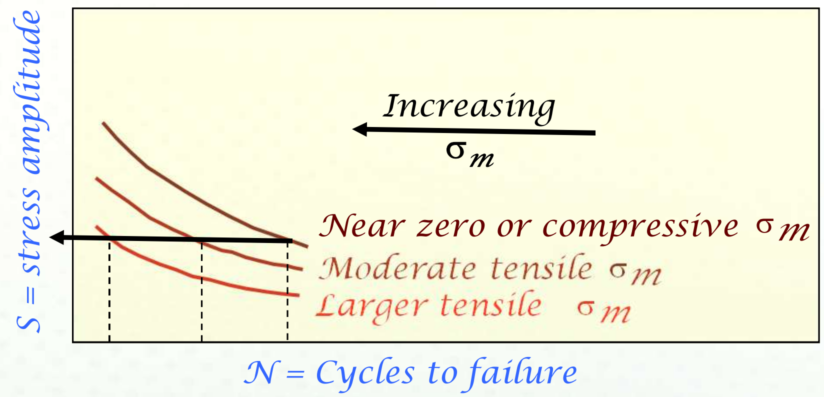
$\frac{da}{dN}$: increase in crack length per loading cycle

- Failed rotating shaft
  - Crack grew even though $K_{max} < K_c$
  - Crack grows faster as
    - ✓ $\Delta\sigma$ increases
    - ✓ Crack gets longer
    - ✓ Loading freq. increases.

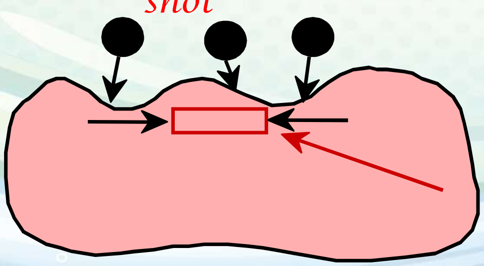


Improving Fatigue Life

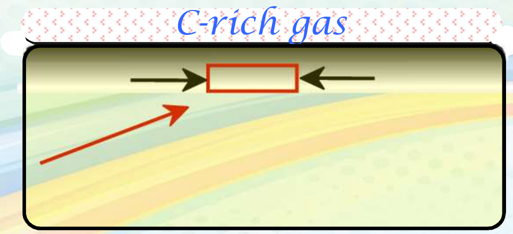
1. *Impose compressive surface stresses (to suppress surface cracks from growing)*



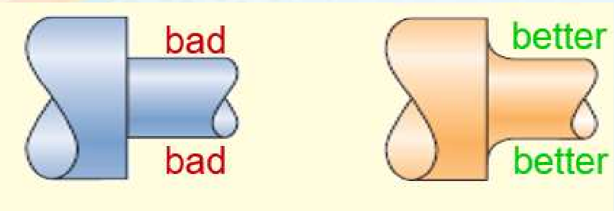
Method 1: Shot peening



Method 2: Carburizing



2. *Remove stress concentrators.*

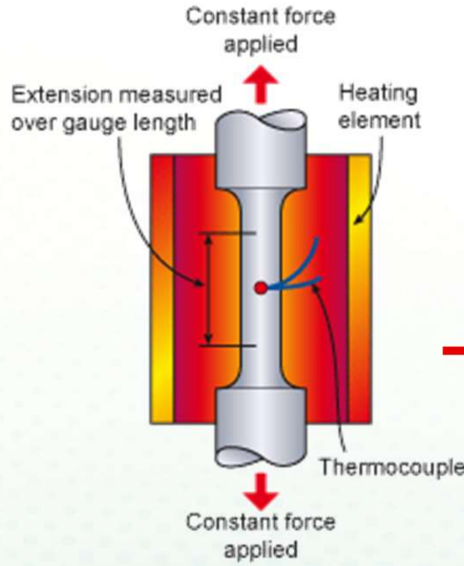


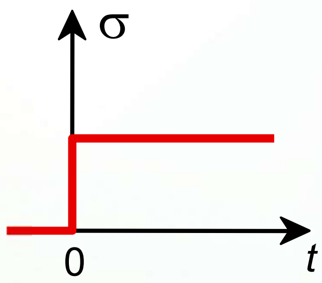
Creep

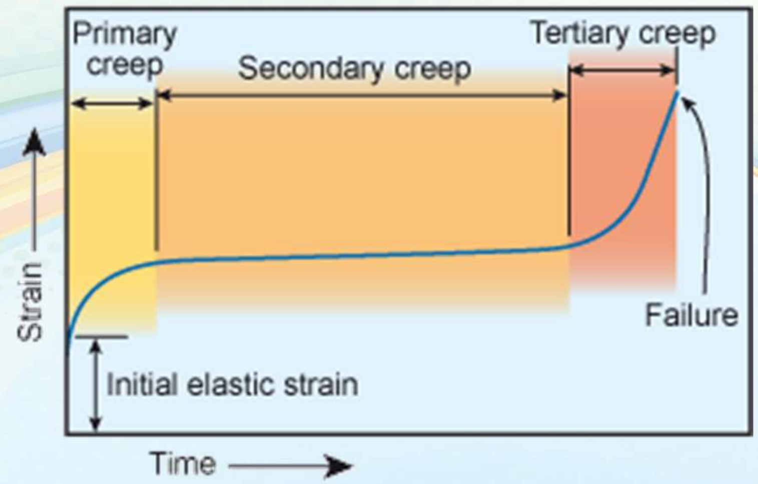
- Creep testing is conducted using a tensile specimen to which a constant stress is applied at a constant temperature, often by the simple method of suspending weights from it.

- The test is recorded on a graph of strain versus time. Sample deformation at a constant stress (s) vs. time

1. Primary Creep: slope (creep rate) decreases with time.
2. Secondary Creep: steady-state, i.e., constant slope ($\Delta\varepsilon/\Delta t$).
3. Tertiary Creep: slope (creep rate) increases with time, i.e. acceleration of rate.

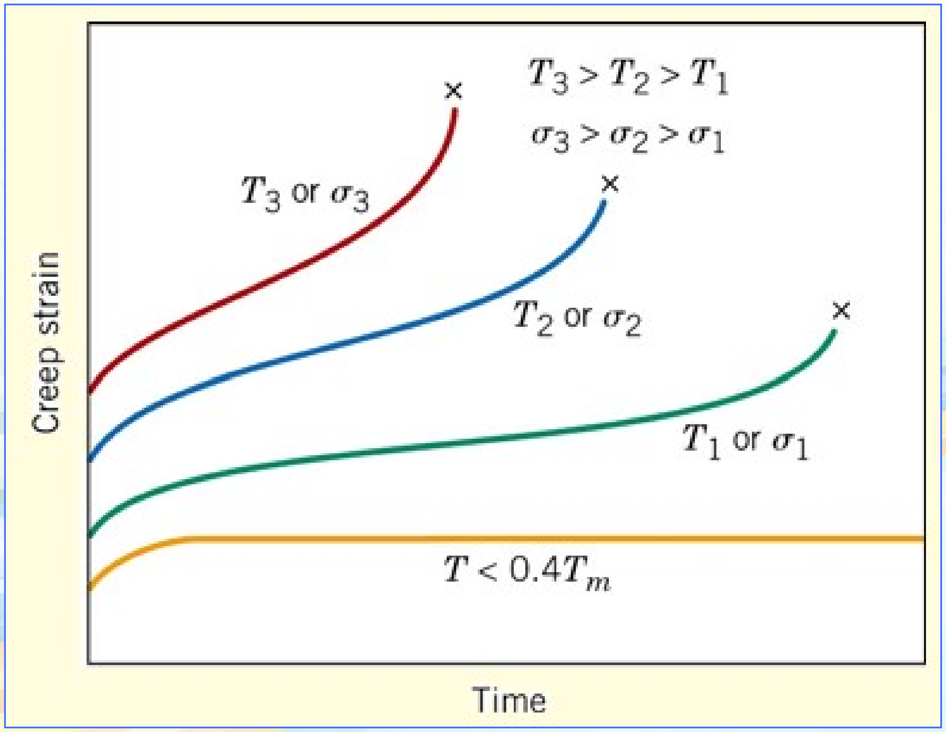






Creep: Temperature Dependence

- *Occurs at elevated temperature, $T > 0.4\ T_m$ (in K)*



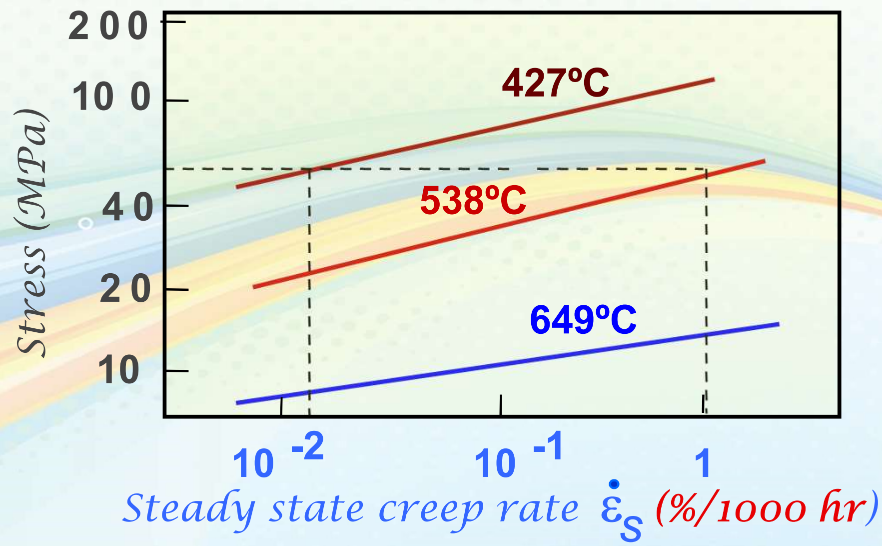
Secondary Creep

- Strain rate is constant at a given T, σ.

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

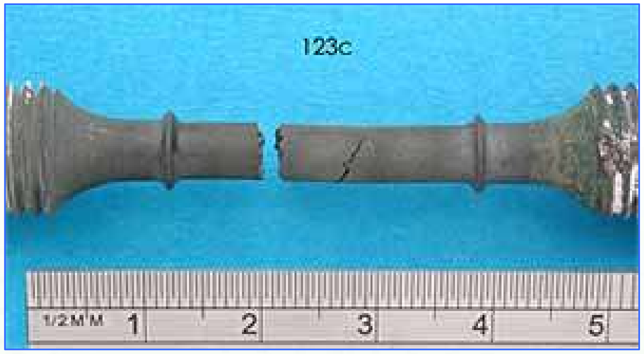
- $\dot{\varepsilon}_s$: strain rate
- K_2: material const.
- σ: applied stress
- n: stress exponent (material parameter)
- Q_c: activation energy for creep (material parameter)

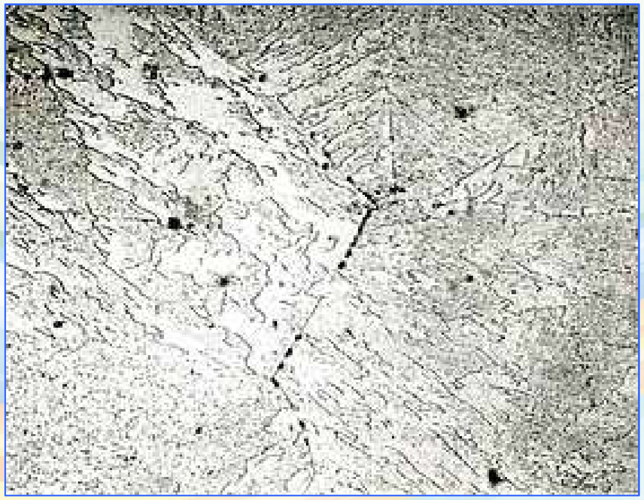
- Strain rate increases with increasing T, σ

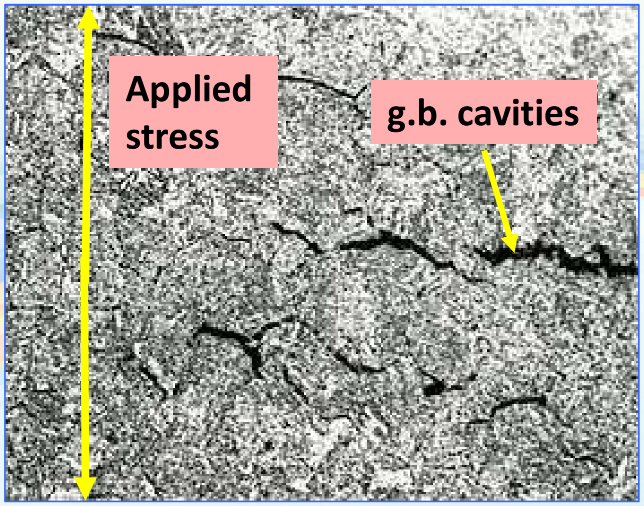


Creep Failure

- *Failure: voids that form on the grain boundaries in the early stages of creep.*







Prediction of Creep Rupture Lifetime

- Estimate rupture time of S-590 Iron at T = 800ºC and a stress value of 20,000 psi

- Time to rupture, t_r

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

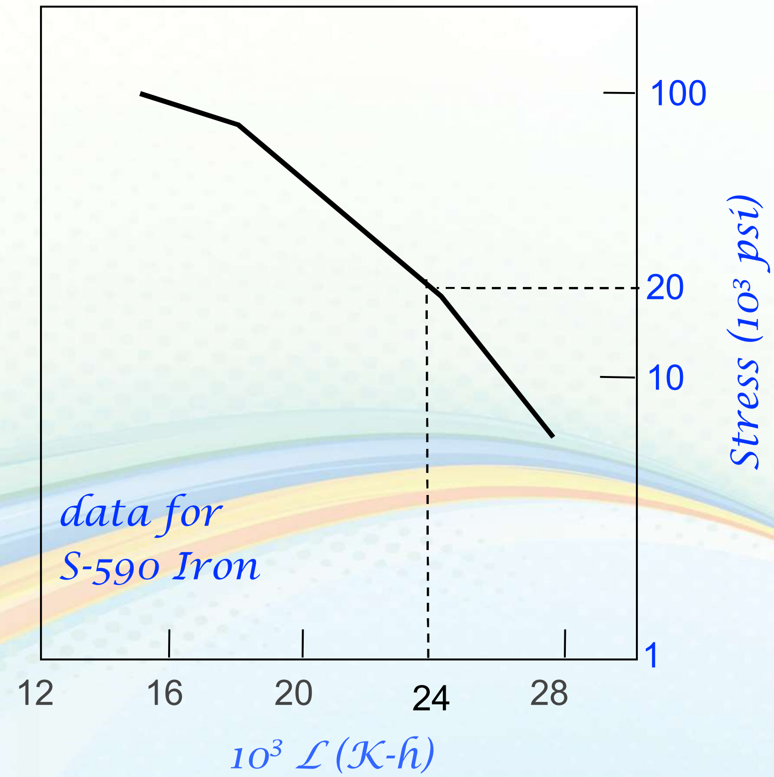
Temperature

Time to failure (rupture)

Function of applied stress

$$(1073\ K)(20 + \log t_r) = 24 \times 10^3$$

Ans: t_r = 233 hr



L: Larson-Miller parameter

Prediction of Creep Rupture Lifetime

- Estimate rupture time of S-590 Iron at $T = 750°C$ and a stress value of 20,000 psi

- Time to rupture, t_r

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

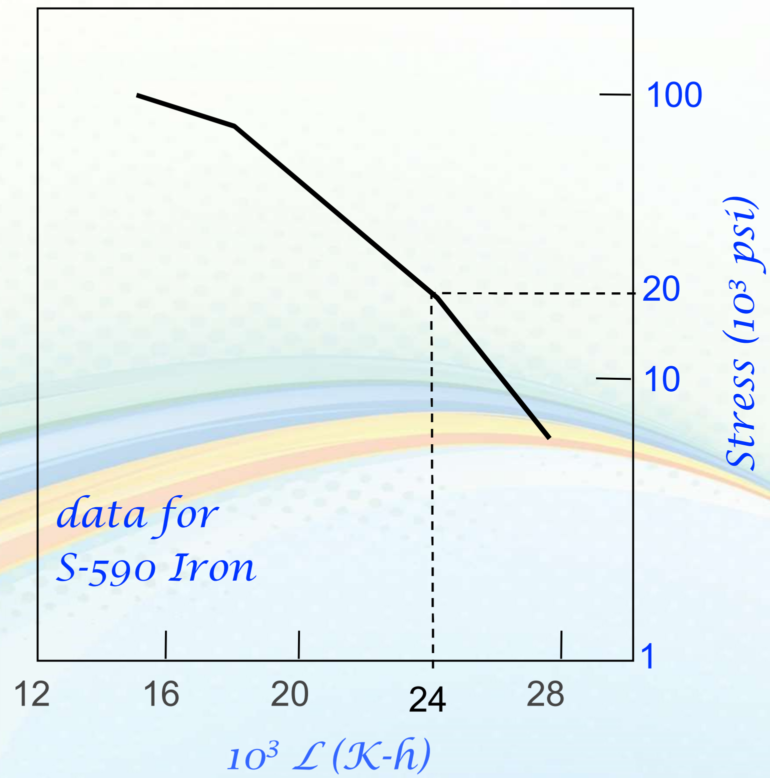
Temperature

Time to failure (rupture)

Function of applied stress

$$(1023\ K)(20 + \log t_r) = 24 \times 10^3$$

Ans: $t_r = 2890$ hr



SUMMARY

- Engineering materials not as strong as predicted by theory.
- Flaws act as stress concentrators that cause failure at stresses lower than theoretical values.
- Sharp corners produce large stress concentrations and premature failure.
- Failure type depends on T and σ:
  - For simple fracture (noncyclic σ and $T < 0.4T_m$), failure stress decreases with:
    - ✓ Increased maximum flaw size,
    - ✓ Decreased T,
    - ✓ Increased rate of loading.
  - For fatigue (cyclic σ):
    - ✓ Cycles to fail decreases as Δσ increases.
  - For creep ($T > 0.4T_m$):
    - ✓ Time to rupture decreases as σ or T increases.