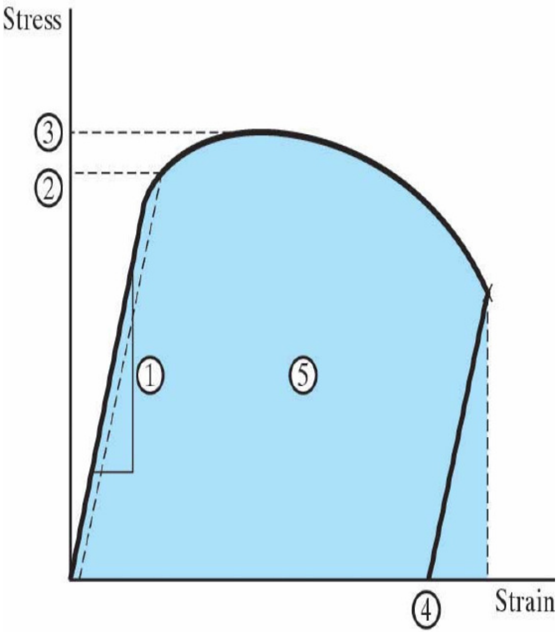
Review : Stress vs Strain



Tensile test yields several useful material properties:

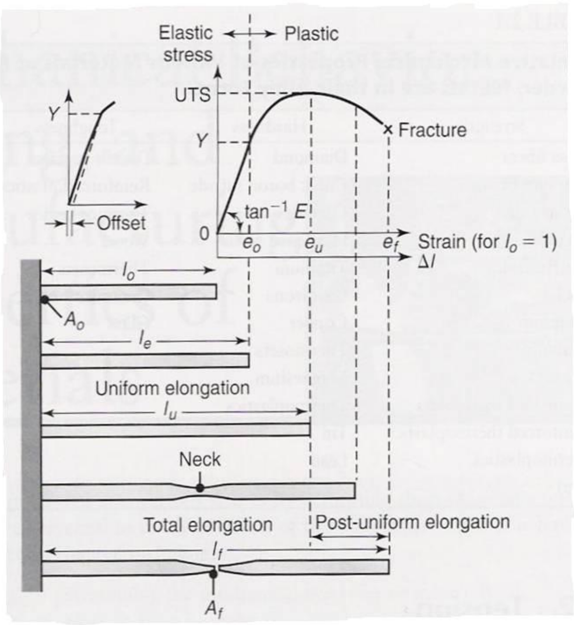
1. **Modulus of Elasticity (E)**
2. **Yield Strength (Y.S.)**
3. **Tensile Strength (T.S.) (Max. Stress)**
4. **Ductility (% elongation at failure)**
5. **Toughness** $= \int \sigma d\varepsilon$
6. **Resilience** $U_r = \int_0^{\varepsilon_y} \sigma d\varepsilon$

U_r = modulus of resilience

Illustrations from Shackelford “Introduction to Materials Sciende for Engineers 6th Ed., Used by permission

Tension

- If the specimen is loaded beyond its UTS it begins to "neck."
- Fracture stress: the engineering stress at fracture.



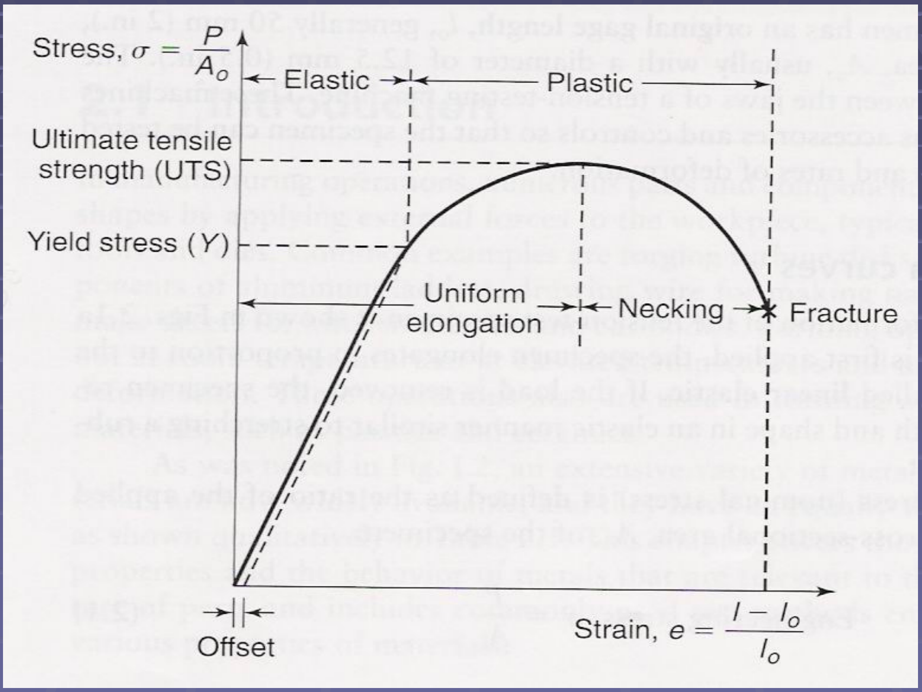
True-Stress and True-Strain

- True-stress: ratio of the load, P, to the instantaneous cross-sectional area, A, of the specimen.
- True-strain: the sum of all the instantaneous engineering strains.
  - True-stress equation: $\sigma = P/A$
  - True-strain equation: $e = \ln(l/l_o)$

Construction of Stress-Strain Curves

- The stress-strain curve can be represented by the equation: $\sigma = Ke^n$
  - K = strength coefficient
  - n = strain hardening exponent

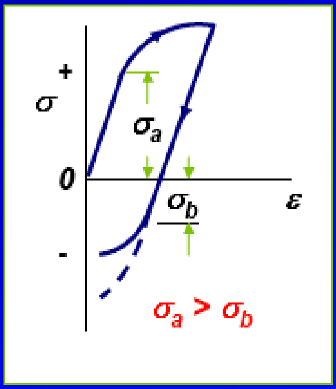
Construction of Stress-Strain Curves



The flow curve

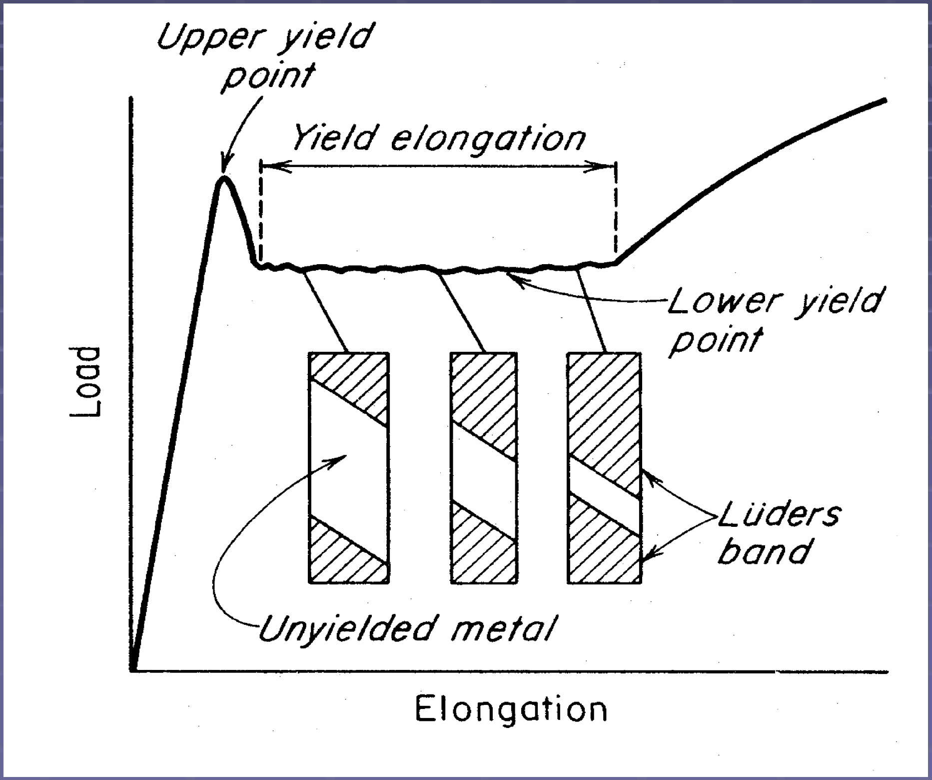
- If specimen is deformed plastically beyond the yield stress in ***tension*** (+), and then in ***compression*** (-), it is found that the yield stress on reloading in compression is less than the original yield stress.

- The dependence of the yield stress on loading path and direction is called the ***Bauschinger effect***. → (however it is neglected in plasticity theories and it is assumed that the yield stress in tension and compression are the same).



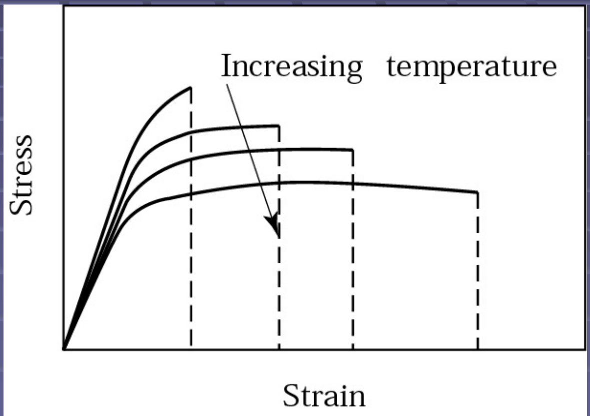
Bauschinger effect

Luders band


Upper yield point
Yield elongation
Lower yield point
Load
Lüders band
Unyielded metal
Elongation

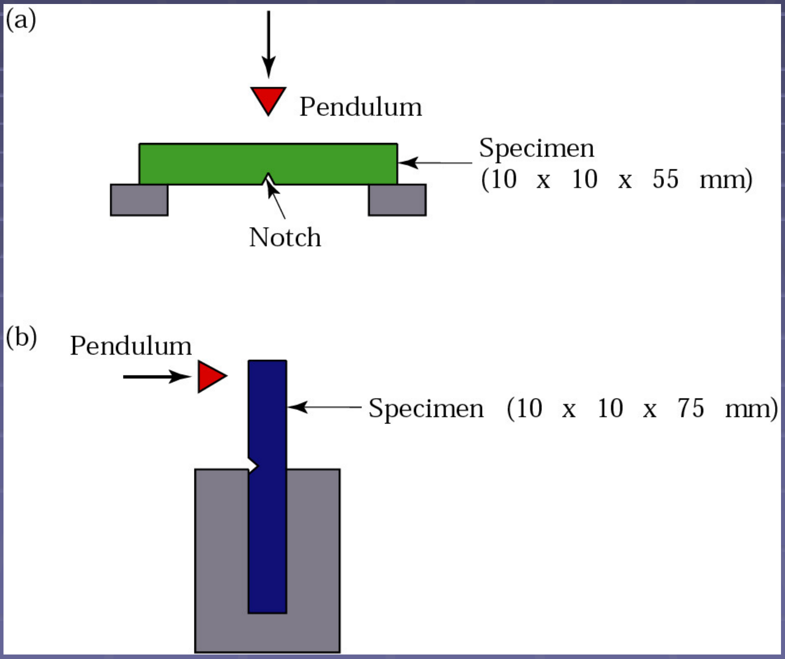
Temperature Effects

- As temperature increases:
  - Ductility and toughness increase.
  - Yield stress and the modulus of elasticity decrease.
- Temperature also affects the strain-hardening exponent of most metals, in that n decreases as temperature increases.



Ductility

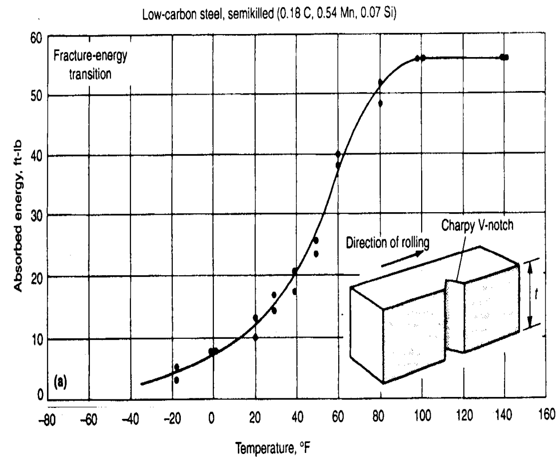
- Ductility: extent of plastic deformation that the material undergoes before fracture.
- Two measures of ductility:
  - Total elongation: $(l_f-l_o)/l_o$ x 100%
  - Reduction of Area: $(A_o-A_f)/A_o$ x 100%


(a)
Pendulum
Specimen
(10 x 10 x 55 mm)
Notch
(b)
Pendulum
Specimen (10 x 10 x 75 mm)

Plot temperature vs. absorbed energy

Draw a curve through the points

DBTT is mean of upper and lower shelf energy



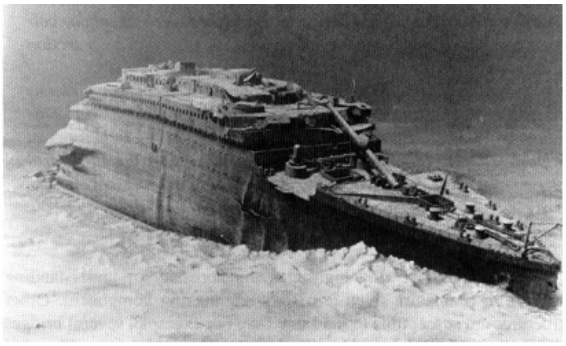
Ductile-to-brittle transition

1. FCC materials do not show DBT
   - Good for cryogenic applications
     - Stainless steel (austenite: fcc)containers
     - for Liq O_2 rocket fuel
     - mild steel not good (α: bcc)

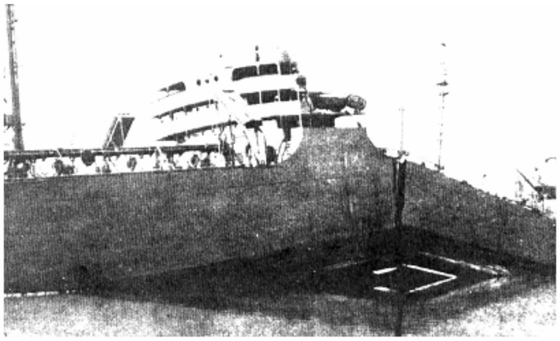
2. Fine grain size give lower transition temperature
3. High strain rate increase the transition temperature
4. Notches increase the transition temperature

Ductile to Brittle Transition Temperature (DBTT)

- **Pre-WWII: The Titanic**



- **WWII: Liberty ships**



Disastrous consequences for a welded transport ship, suddenly split across the entire girth of the ship (40˚F). The vessels were constructed from steel alloys that exhibit a DBTT ≈ room temp

Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(a), p. 262, John Wiley and Sons, Inc., 1996. (Orig. source: Dr. Robert D. Ballard, *The Discovery of the Titanic.*)

Fatigue

- Fatigue is the name given to failure in response to alternating loads (as opposed to monotonic straining).
- Instead of measuring the resistance to fatigue failure through an upper limit to strain (as in ductility), the typical measure of fatigue resistance is expressed in terms of numbers of cycles to failure. For a given number of cycles (required in an application), sometimes the stress (that can be safely endured by the material) is specified.

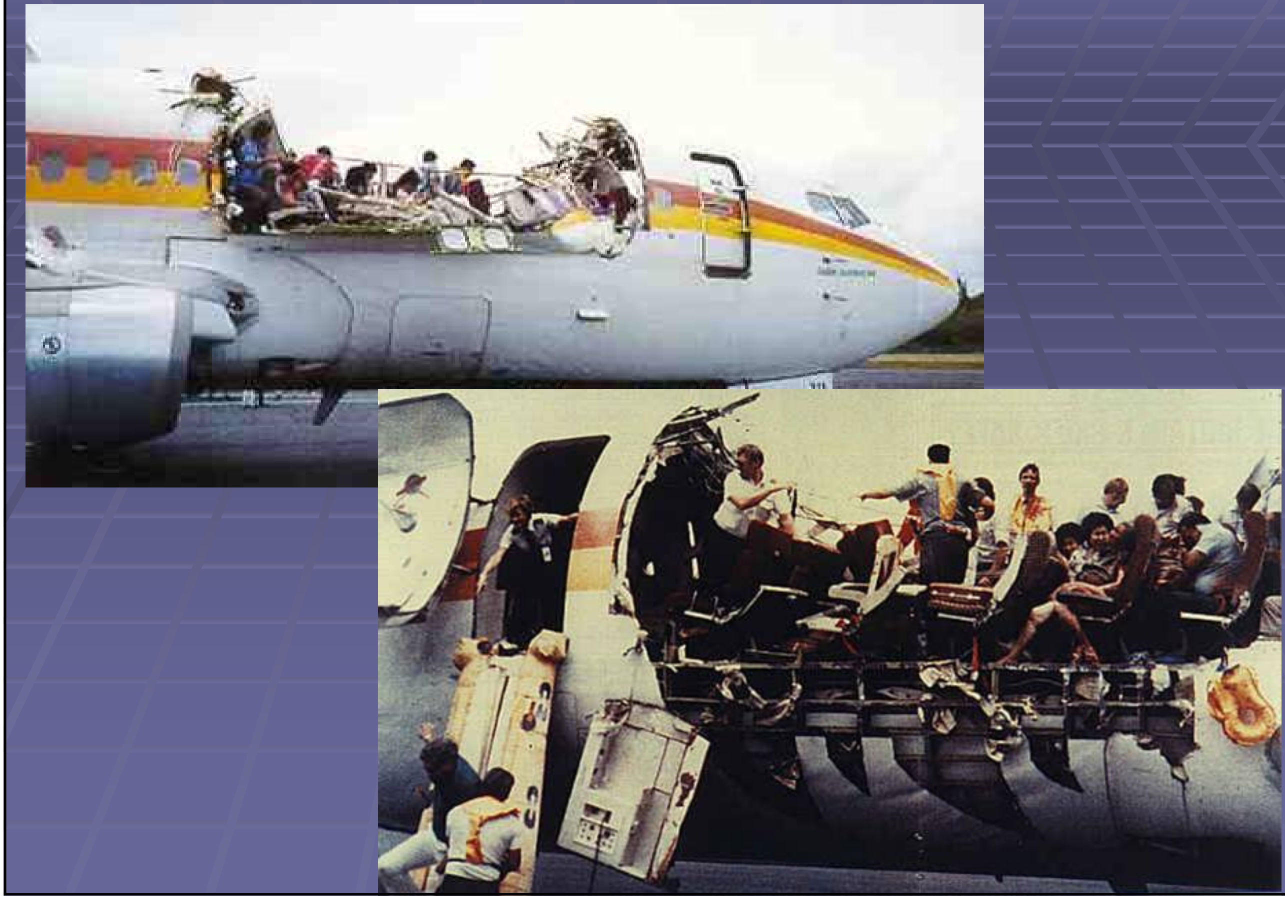
Fatigue: general characteristics

- **Primary design criterion in rotating parts.**
- Fatigue as a name for the phenomenon based on the notion of a material becoming “tired”, i.e. failing at less than its nominal strength.
- Cyclical strain (stress) leads to fatigue failure.
- Occurs in metals and polymers but rarely in ceramics.

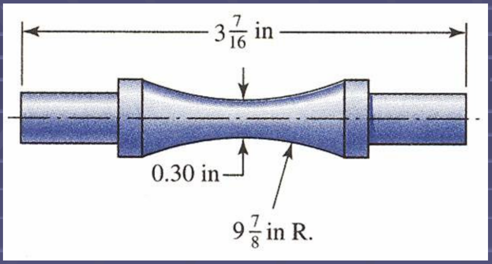
Fatigue: general characteristics

- Most applications of structural materials involve cyclic loading; any net tensile stress leads to fatigue.
- Fatigue failure surfaces have three characteristic features: [see next slide, also Courtney figs. 12.1, 12.2]
  - A (near-)surface defect as the origin of the crack
  - Striations corresponding to slow, intermittent crack growth
  - Dull, fibrous brittle fracture surface (rapid growth).
- Life of structural components generally limited by cyclic loading, not static strength.
- Most environmental factors shorten life.

Hawaii, Aloha Flight 243, a Boeing 737, an upper part of the plane's cabin area rips off in mid-flight. Metal fatigue was the cause of the failure.

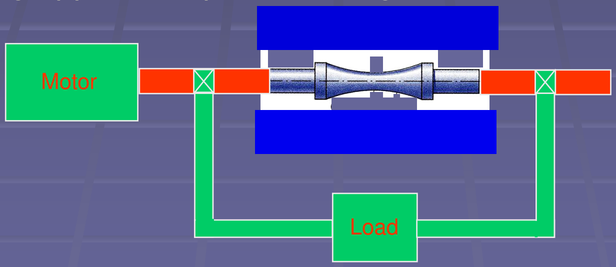


Fatigue Failure, S-N Curve



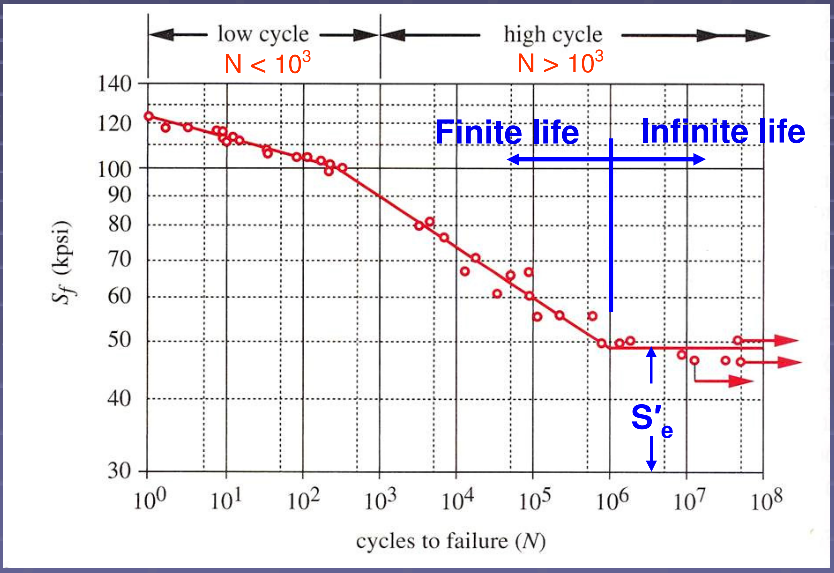
Test specimen geometry for R.R. Moore rotating beam machine. The surface is polished in the axial direction. A constant bending load is applied.

Typical testing apparatus, pure bending



Rotating beam machine – applies fully reverse bending stress

Fatigue Failure, S-N Curve



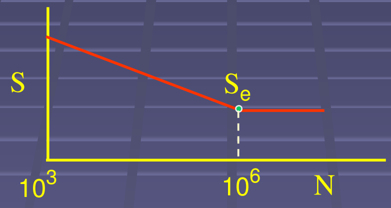
S_e' = endurance limit of the specimen

Correction Factors for Specimen's Endurance Limit

For materials exhibiting a knee in the S-N curve at 10^6 cycles

S_e' = endurance limit of the specimen (infinite life > 10^6)

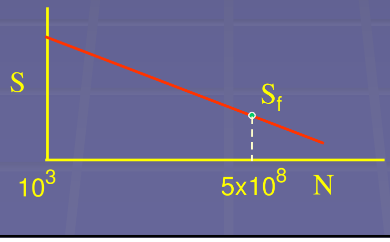
S_e = endurance limit of the actual component (infinite life > 10^6)



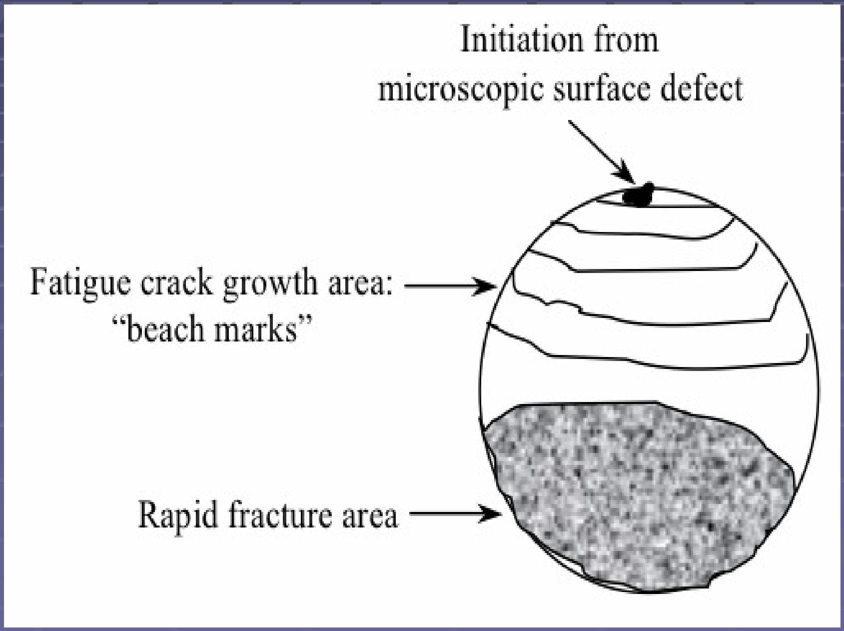
For materials that do not exhibit a knee in the S-N curve, the infinite life taken at $5x10^8$ cycles

S_f' = fatigue strength of the specimen (infinite life > $5x10^8$)

S_f = fatigue strength of the actual component (infinite life > $5x10^8$)

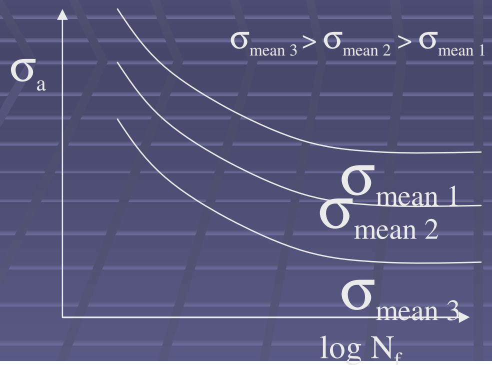


Crack growth




Origin of fatigue crack

Fatigue testing, S-N curve



The greater the number of cycles in the loading history, the smaller the stress that the material can withstand without failure.

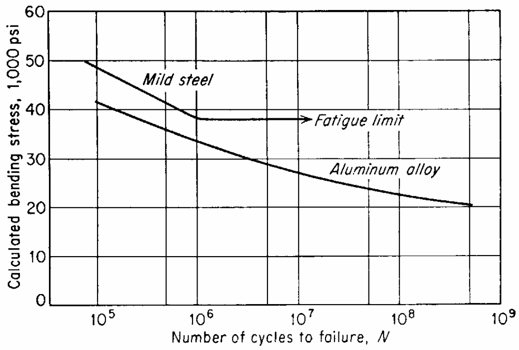


Figure 12-3 Typical fatigue curves for ferrous and nonferrous metals.

Note the presence of a fatigue limit in many steels and its absence in aluminum alloys.

[Dieter]

Endurance Limits

- Some materials exhibit *endurance limits*, i.e. a stress below which the life is infinite: [fig. 12.8]
    - Steels typically show an endurance limit, = 40% of yield; this is typically associated with the presence of a solute (carbon, nitrogen) that pines dislocations and prevents dislocation motion at small displacements or strains (which is apparent in an upper yield point).
    - Aluminum alloys do not show endurance limits; this is related to the absence of dislocation-pinning solutes.
- At large N_f, the lifetime is dominated by nucleation.
    - Therefore strengthening the surface (shot peening) is beneficial to delay crack nucleation and extend life.

Fatigue fracture surface

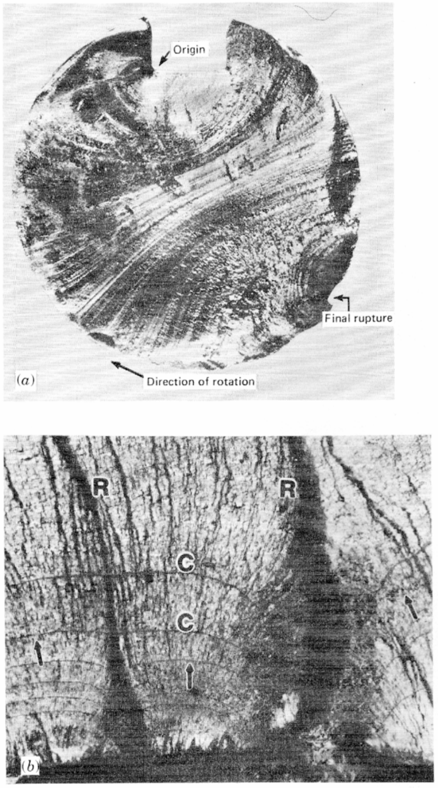


FIGURE 12.3 Fatigue fracture markings. (*a*) Rotating steel shaft. Center of curvature of earlier "beach markings" locate crack origin at corner of keyway.[2] (By permission from D. J. Wulpi, *How Components Fail*, copyright American Society for Metals, 1966.) (*b*) Clam shell markings (C) and ratchet lines (R) in aluminum. Arrows indicate crack propagation direction (Photo courtesy of R. Jaccard). (*c*) Fatigue bands in high-impact polystyrene toilet seat. (*d*) Beach markings in South Carolina.

[Hertzberg]

Fatigue crack stages

Stage 1

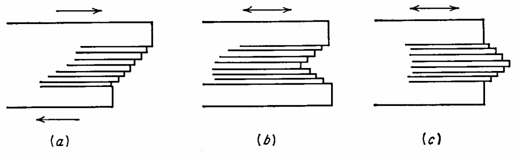


Figure 12-15 W. A. Wood's concept of microdeformation leading to formation of fatigue crack. (*a*) Static deformation; (*b*) fatigue deformation leading to surface notch (intrusion); (*c*) fatigue deformation leading to slip-band extrusion.

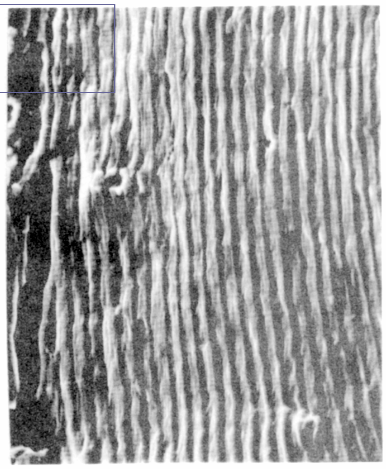


Figure 12-16 Fatigue striations in beta-annealed Ti-6Al-4V alloy (2000×). *(Courtesy of R. A. Bayles, Naval Research Laboratory.)*

[Dieter]

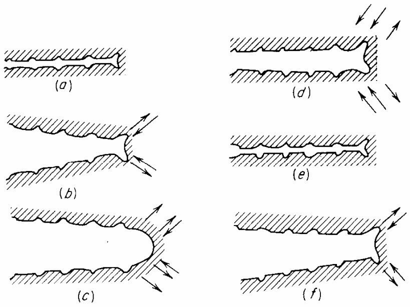
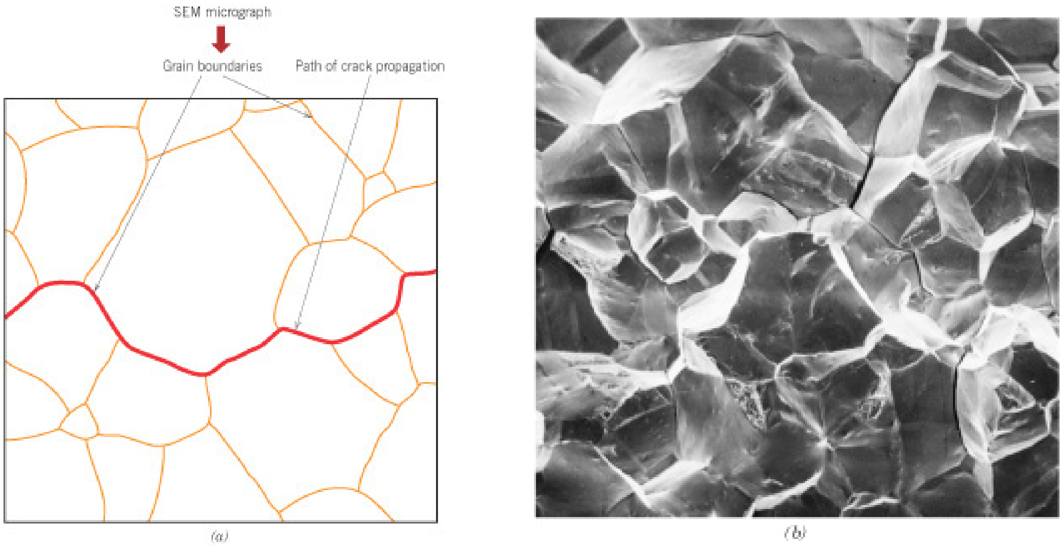


Figure 12-17 Plastic blunting process for growth of stage II fatigue crack. *(From C. Laird, ASTM Spec. Tech. Publ. 415, p. 136, 1967.)*

Fatigue Crack Nucleation

- Flaws, cracks, voids can all act as crack nucleation sites, especially at the surface.
- Therefore, smooth surfaces increase the time to nucleation; notches, stress risers decrease fatigue life.
- Dislocation activity (slip) can also nucleate fatigue cracks.

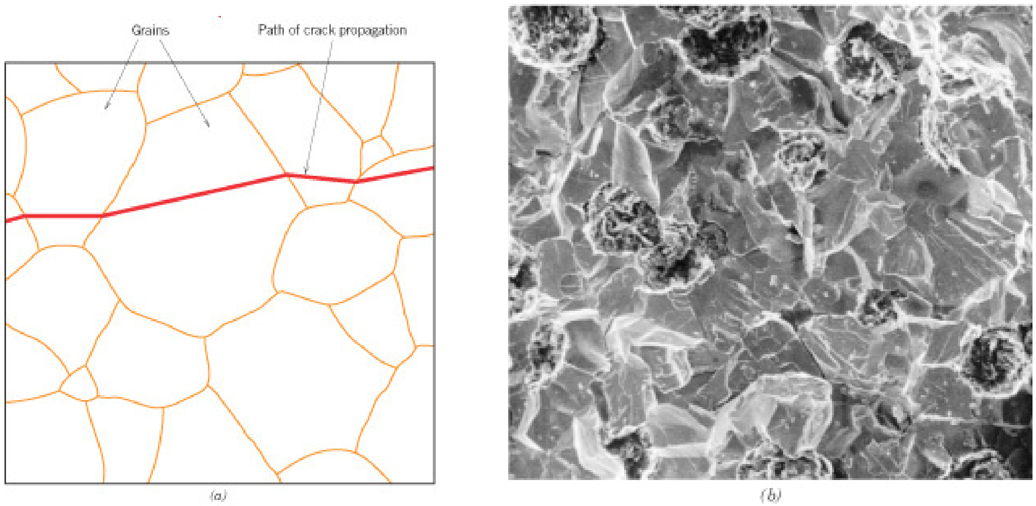
Intergranular Fracture



- Intergranular failure is typically due to elemental depletion (chromium) at the grain boundaries or some type of weakening of the grain boundary due to chemical attack, oxidation, embrittlement.

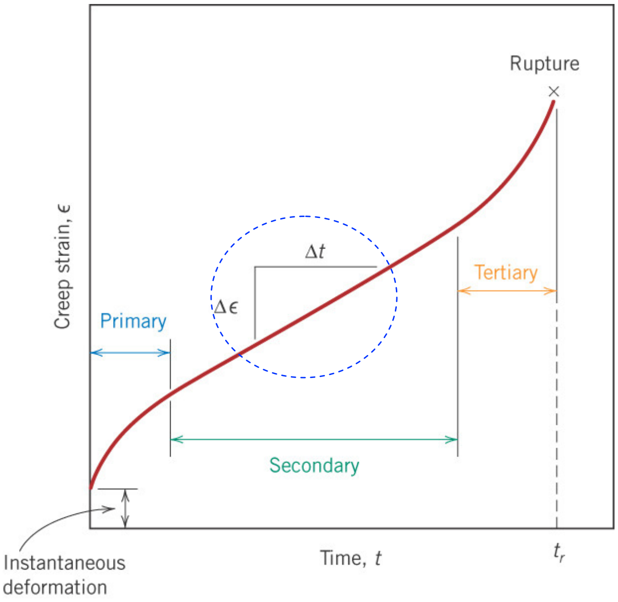
Transgranular Fracture

- Cleavage - in most brittle crystalline materials, crack propagation that results from the repeated breaking of atomic bonds along specific planes.
- This leads to transgranular fracture where the crack splits (cleaves) through the grains.



Creep

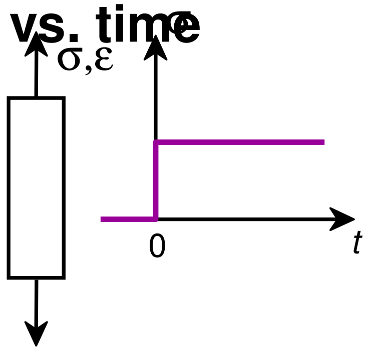
- A typical creep test consists of subjecting a specimen to a constant load or stress while maintaining constant temperature.
- Upon loading, there is instant elastic deformation. The resulting creep curve consists of 3 regions: primary or transient creep adjusts to the creep level (creep rate may decrease); secondary creep- steady state-constant creep rate, fairly linear region (strain hardening and recovery stage); tertiary creep, there is accelerated rate of strain until rupture (grain boundary separation, internal crack formation, cavities and voids).

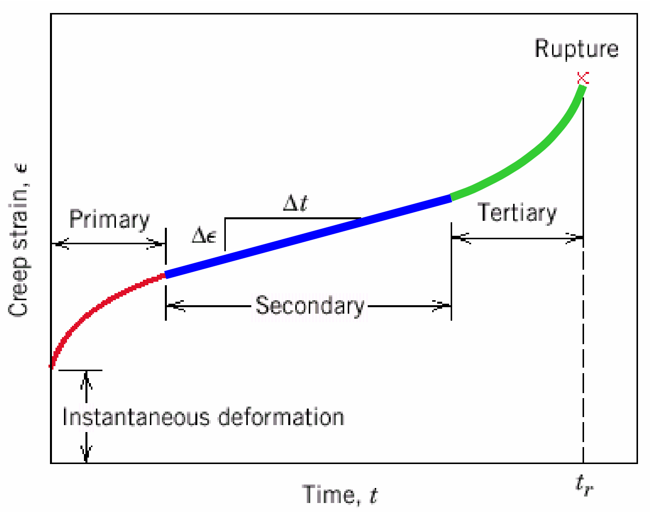


Creep strain vs time at constant load and constant elevated temperature. Minimum creep rate (steady-state creep rate), is the slope of the linear segment in the secondary region. Rupture lifetime t_r is the total time to rupture.

Creep

Sample deformation at a constant stress (σ) vs. time





Primary Creep: slope (creep rate) decreases with time.

Secondary Creep: steady-state i.e., constant slope.

Tertiary Creep: slope (creep rate) increases with time, i.e. acceleration of rate.

Fracture Modes

- Simple fracture is the separation of a body into 2 or more pieces in response to an applied stress that is static (constant) and at temperatures that are low relative to the T_m of the material.
- Classification is based on the ability of a material to experience plastic deformation.
- Ductile fracture
  - Accompanied by significant plastic deformation
- Brittle fracture
  - Little or no plastic deformation
  - Sudden, catastrophic

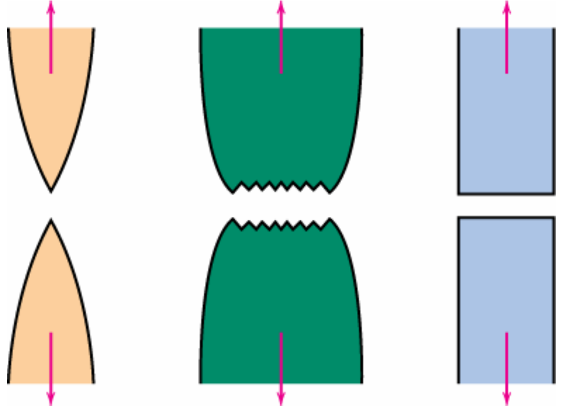
Fracture Mechanism

Imposed stress ⇨ Crack Formation ⇨ Propagation

- Ductile failure has extensive plastic deformation in the vicinity of the advancing crack. The process proceeds relatively slow (stable). The crack resists any further extension unless there is an increase in the applied stress.
- In brittle failure, cracks may spread very rapidly, with little deformation. These cracks are more unstable and crack propagation will continue without an increase in the applied stress.

Ductile vs Brittle Failure

Fracture behavior:	Very Ductile	Moderately Ductile	Brittle



%*AR* or %*EL*	Large	Moderate	Small

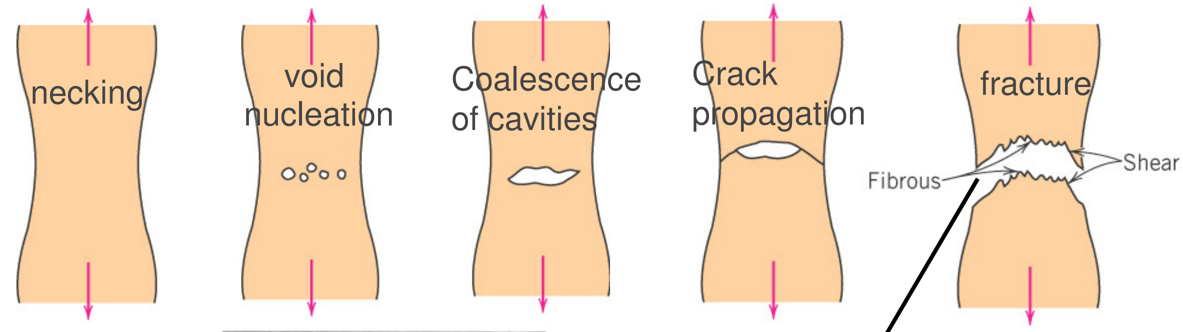
- Ductile fracture is usually more desirable than brittle fracture.

Ductile:
Warning before fracture

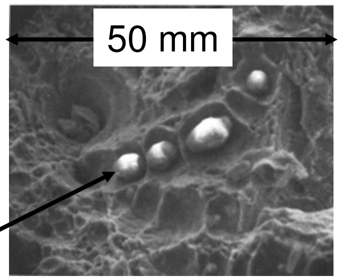
Brittle:
No warning

Moderately Ductile Failure

- Evolution to failure:

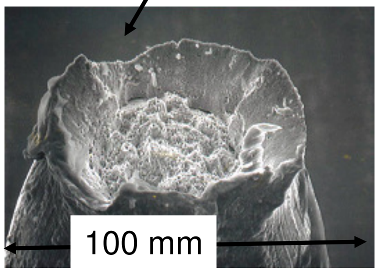


- Resulting fracture surfaces (steel)



particles serve as void nucleation sites.

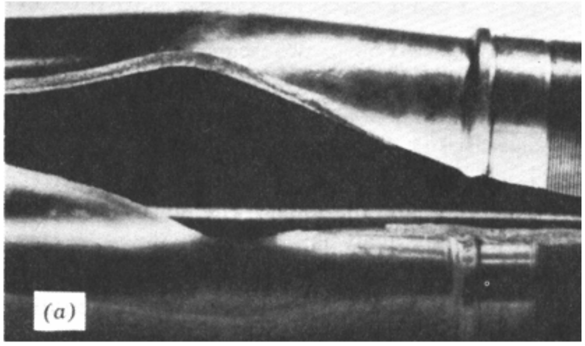
From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 11.28, p. 294, John Wiley and Sons, Inc., 1987. (Orig. source: P. Thornton, *J. Mater. Sci.*, Vol. 6, 1971, pp. 347-56.)



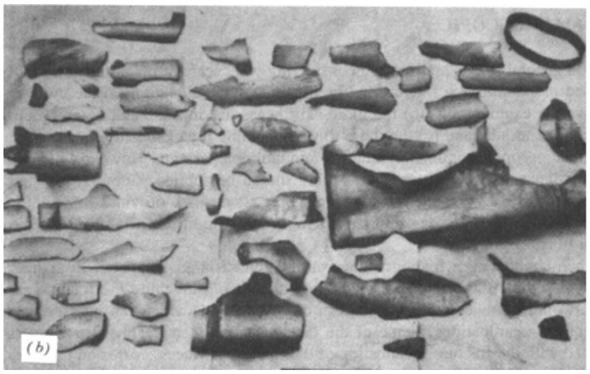
Fracture surface of tire cord wire loaded in tension. Courtesy of F. Roehrig, CC Technologies, Dublin, OH. Used with permission.

Example: Pipe Failures

- **Ductile failure:**
  -- one piece
  -- large deformation



- **Brittle failure:**
  -- many pieces
  -- small deformations



Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66 John Wiley and Sons, Inc., 1987. Used with permission.

Ductile vs. Brittle Failure

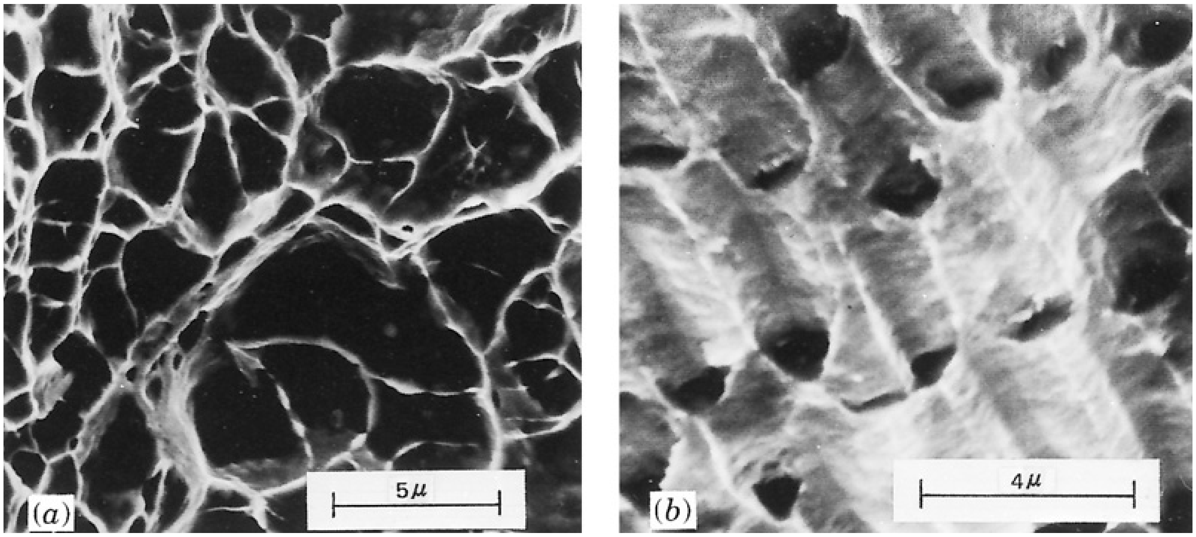
(a)

cup-and-cone fracture

(b)

brittle fracture

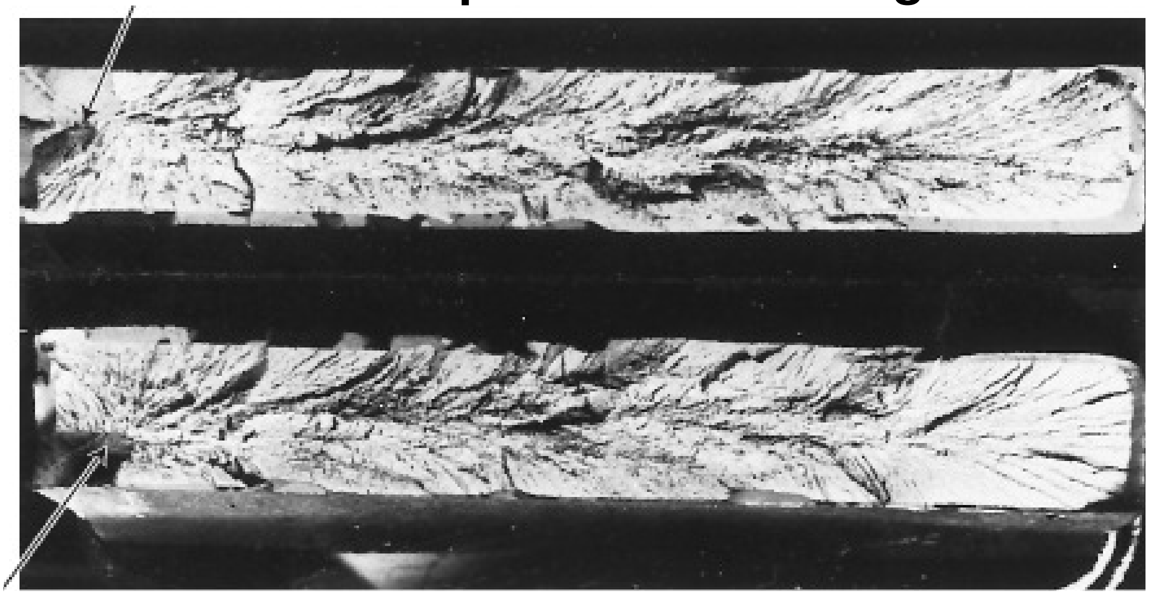
Ductile Failure



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

Brittle Fracture

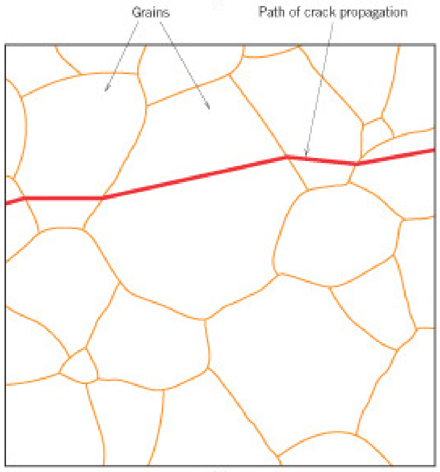
Arrows indicate point at failure origination



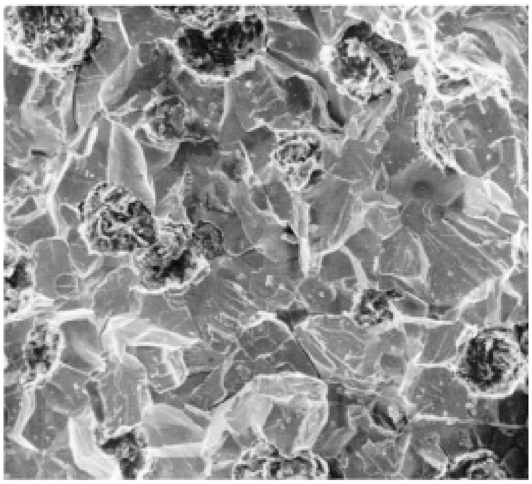
Distinctive pattern on the fracture surface: V-shaped “chevron” markings point to the failure origin.

Transgranular Fracture

- Cleavage - in most brittle crystalline materials, crack propagation that results from the repeated breaking of atomic bonds along specific planes.
- This leads to transgranular fracture where the crack splits (cleaves) through the grains.

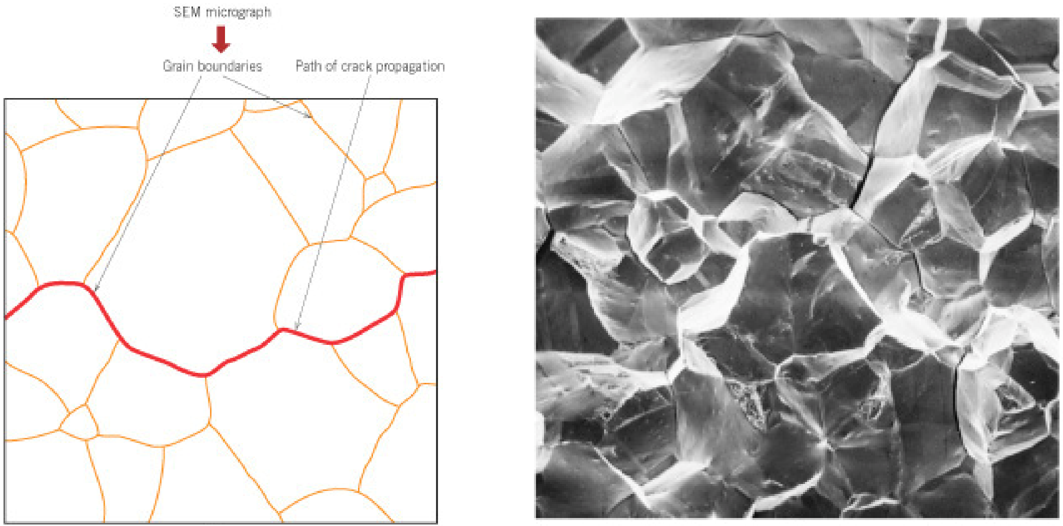


(a)



(b)

Intergranular Fracture



(a) (b)

- Intergranular failure is typically due to elemental depletion (chromium) at the grain boundaries or some type of weakening of the grain boundary due to chemical attack, oxidation, embrittlement.

Ductile vs Brittle

- The effect of a stress raiser is more significant in brittle than in ductile materials.
- For a ductile material, plastic deformation results when the maximum stress exceeds the yield strength.
- This leads to a more uniform distribution of stress in the vicinity of the stress raiser; the maximum stress concentration factor will be less than the theoretical value.
- In brittle materials, there is no redistribution or yielding.

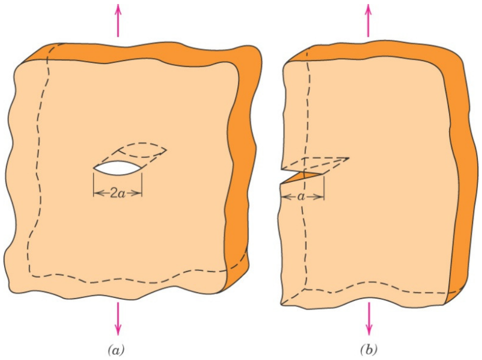
Critical Stress

- All brittle materials contain a population of small cracks and flaws that have a variety of sizes, geometries and orientations.
- When the magnitude of a tensile stress at the tip of one of these flaws exceeds the value of this critical stress, a crack forms and then propagates, leading to failure.
- Fracture toughness measures a material's resistance to brittle fracture when a crack is present.

Fracture Toughness Dependence on Critical Stress for Crack Propagation

The critical stress for crack propagation in brittle materials:

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



where

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

For ductile => replace γ_s by $\gamma_s + \gamma_p$ where γ_p is plastic deformation energy