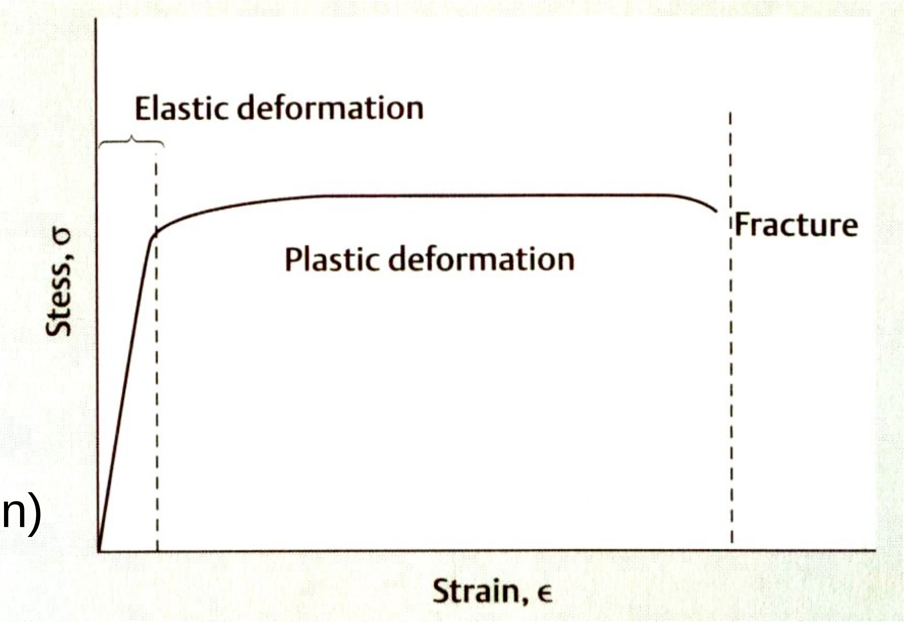
Chapter 7. Mechanical Properties of Metals II
Fracture and Failure

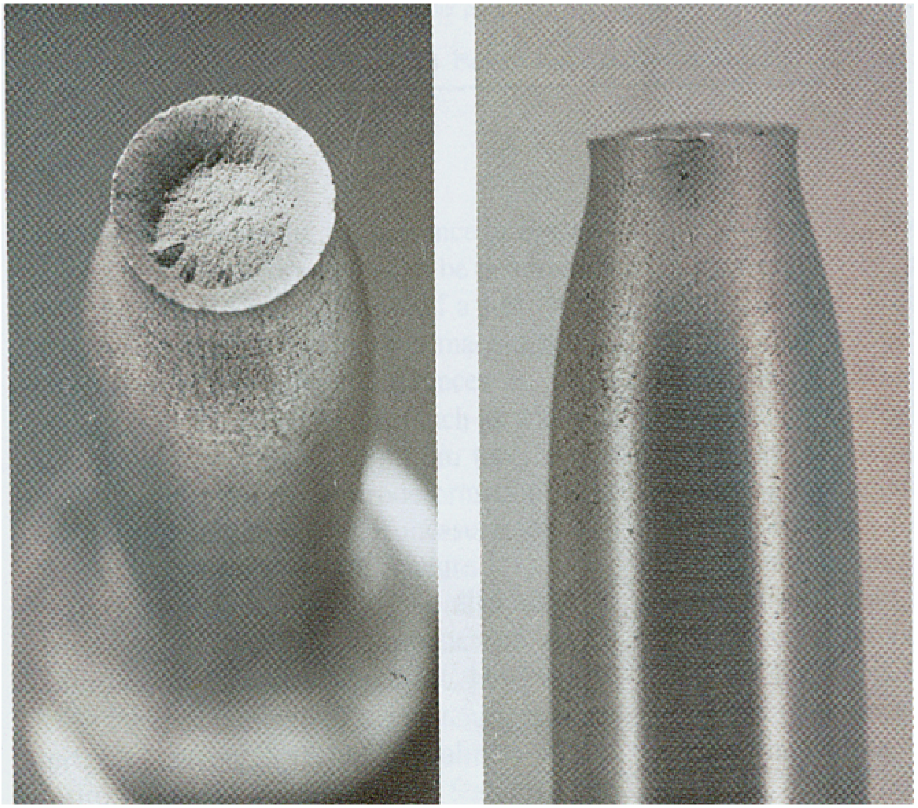
1. Fracture
   - ductile fracture
   - brittle fracture
   - ductile to brittle transition T
2. Fatigue:
   - fatigue failure
   - fatigue crack growth rate
3. Creep (time-dependent deformation)
   - creep rate
   - Larsen-Miller parameter



How to improve mechanical characteristics?

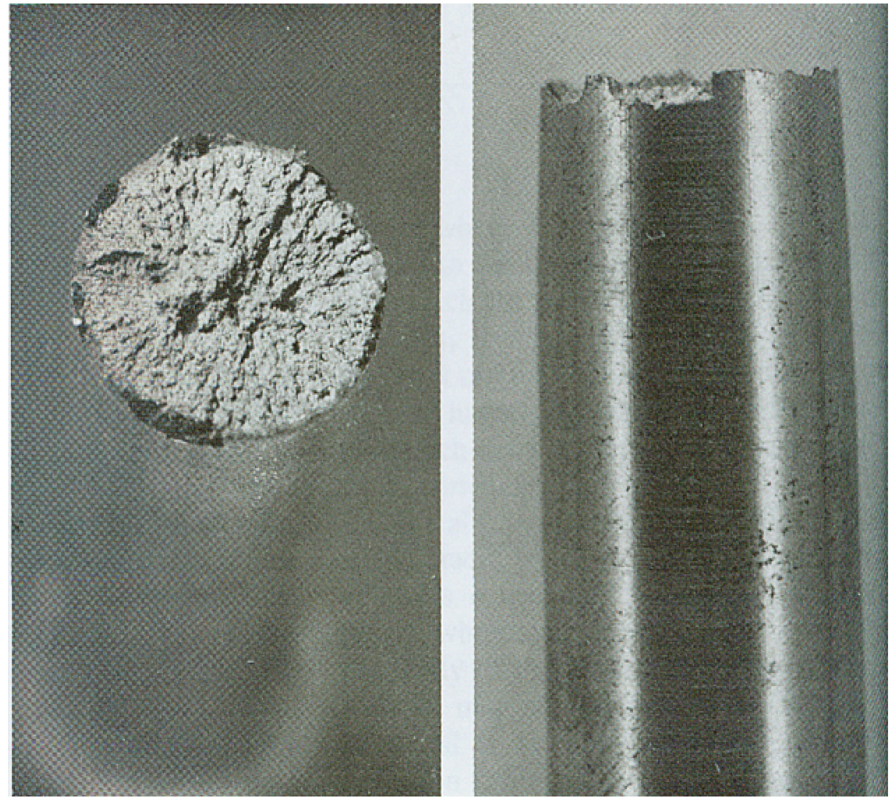
Ductile and Brittle Fractures

Fracture results in separation of stressed solid into two or more parts



Ductile fracture

- after extensive plastic deformation
- slow defect/crack propagation



Brittle Fracture

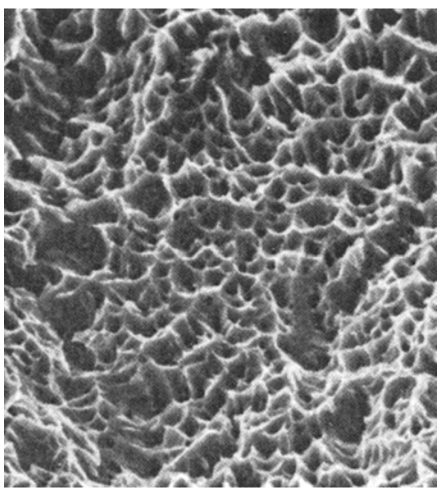
- along crystallographic (cleavage) planes
- rapid crack propagation

7.1 Fracture of Metals – Ductile Fracture

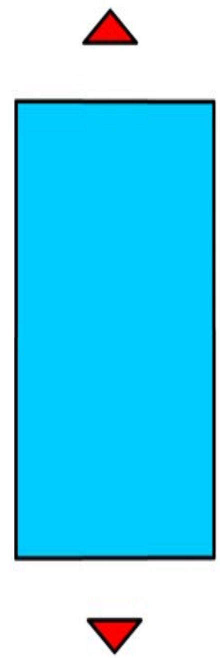
Ductile fracture: high plastic deformation & slow crack propagation

Three steps:

- Specimen forms neck and cavities within neck
- Cavities form crack and crack propagates towards surface, perpendicular to stress
- Direction of crack changes to 45^0 resulting in *cup-cone fracture*



Scanning electron micrograph showing conical equaxial features produced during the fracture of a steel sample



Brittle Fracture

No significant plastic deformation before fracture

Common at high strain rates and low T

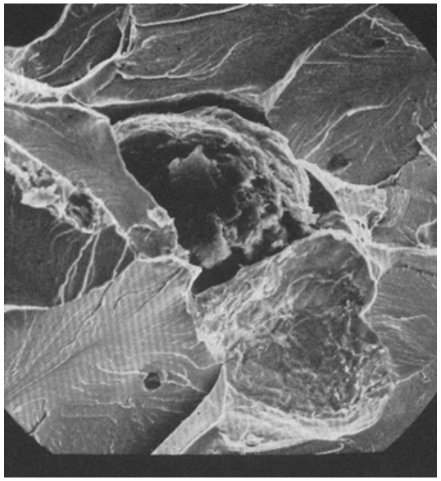
- **Three stages**

  1. Plastic deformation concentrates dislocations along slip planes
  2. Microcracks nucleate due to shear stress where dislocations are blocked
  3. Crack propagates to fracture

Ex.: hcp Zn single crystal under high stress along {0001} plane

- Due to defects like:
  - porosity
  - tears and cracks
  - corrosion damage
  - embrittlement due to atomic hydrogen

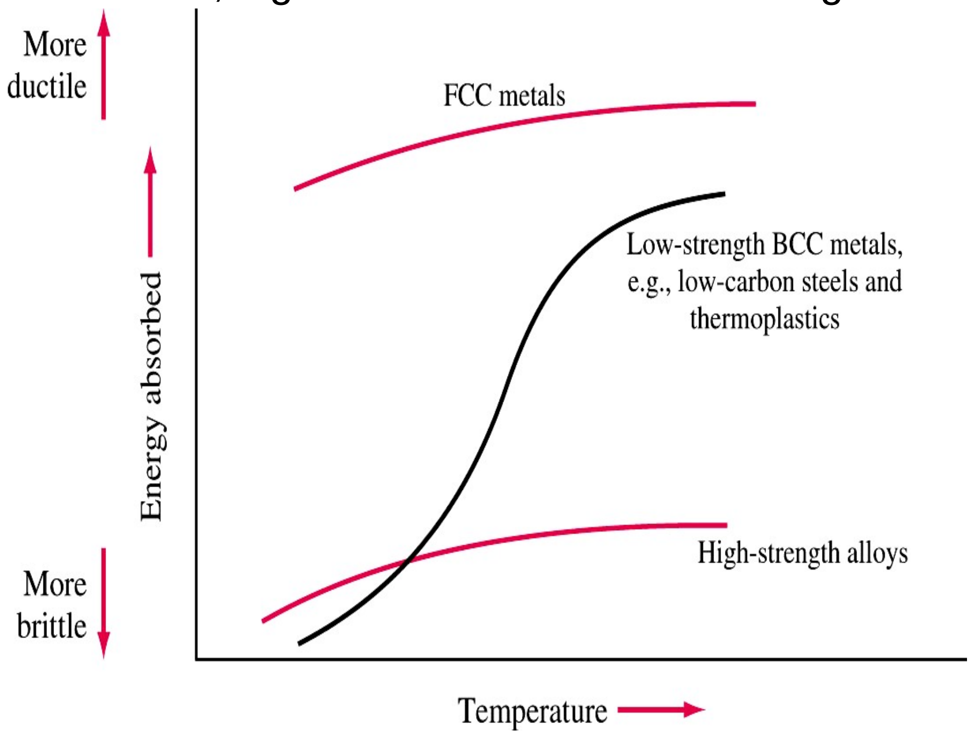
Most brittle fractures are transgranular

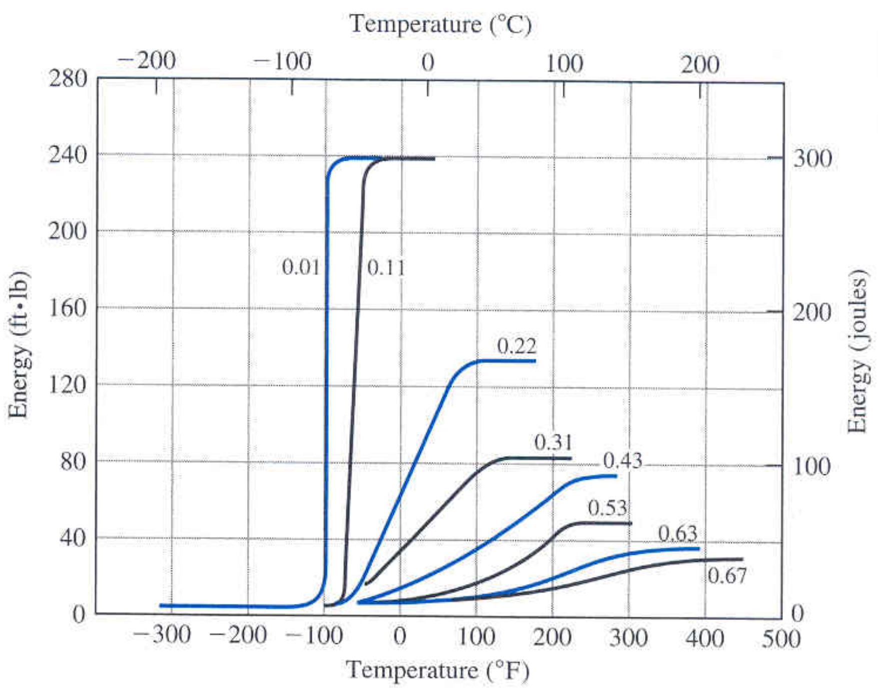


Scanning electron micrograph showing brittle fracture in ferritic ductile iron

Ductile to Brittle Transition (DBT) Temperature

At low T, high stress levels or fast loading rates ductile to brittle transition takes place





Operation at low temperatures

Sinking of Titanic: Titanic was made up of steel which has low DBT temperature. On the day of sinking, sea temperature was -2^0C which made the structure highly brittle and susceptible to more damage

Fracture Toughness

Cracks and flaws cause **stress concentration**

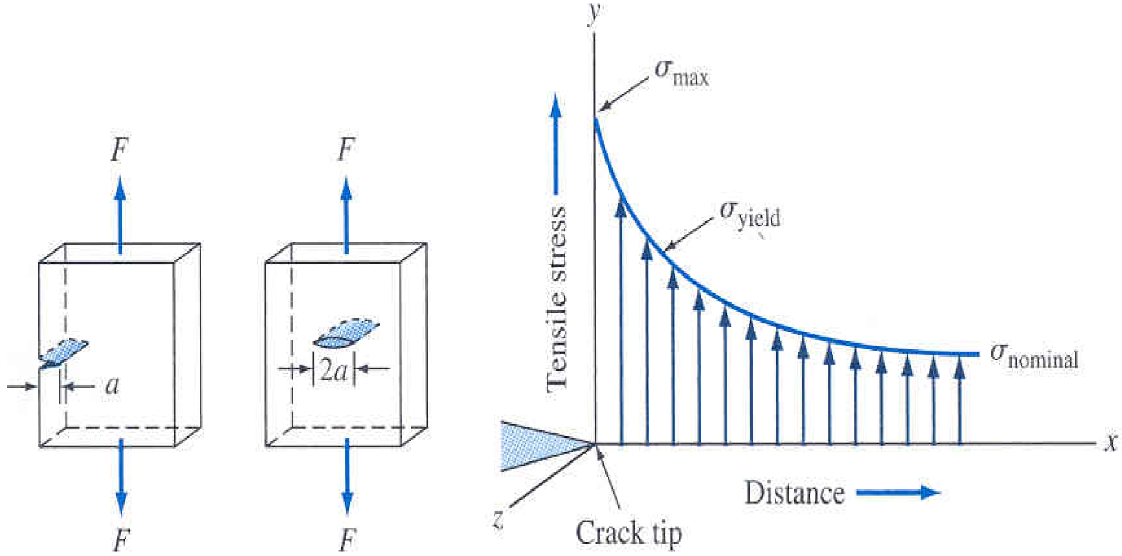


Figure 6.17

$$K_1 = Y\sigma\sqrt{\pi a}$$

K_1 - Stress intensity factor

σ - Applied stress

a - edge crack length

Y - geometric constant

K_{Ic} - critical value of stress intensity factor (fracture toughness)

$$= Y\sigma_f\sqrt{\pi a}$$

Measuring Fracture Toughness: notch is machined in a specimen of thickness B

B >> a plain strain condition.

B = 2.5(K_{Ic}/Yield strength)^2

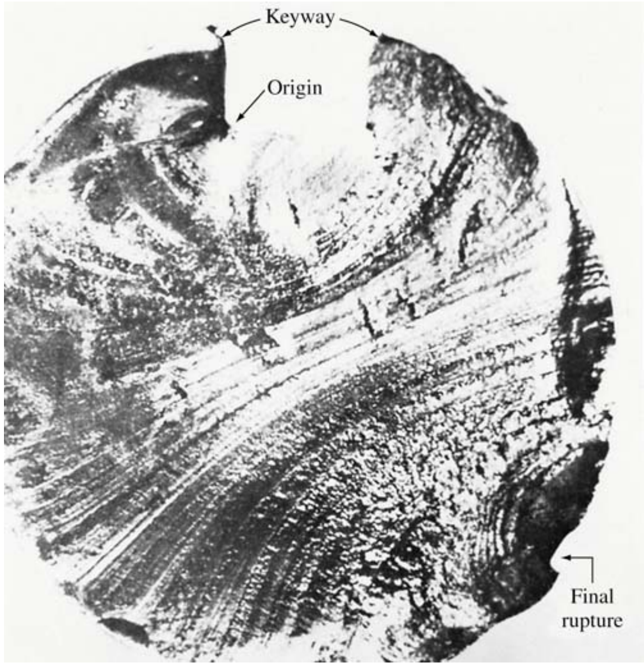
Specimen is tensile tested

Higher the K_{Ic} value, more ductile the metal is

7.2 Fatigue of Metals

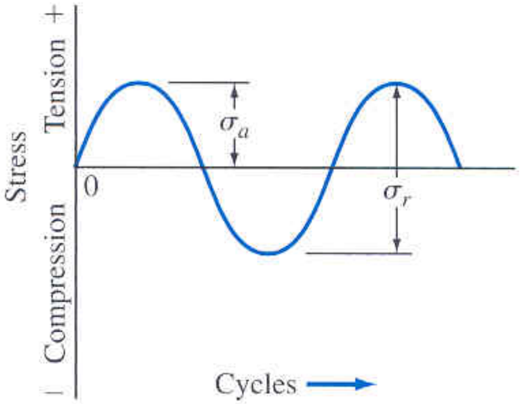
Fatigue: the phenomenon leading to fracture under repeated stresses having the maximum value less than the ultimate strength of the material

- Metals often fail at much lower stress at cyclic loading compared to static loading
- Crack nucleates at region of stress concentration and propagates due to cyclic loading
- Failure occurs when cross sectional area of the metal too small to withstand load

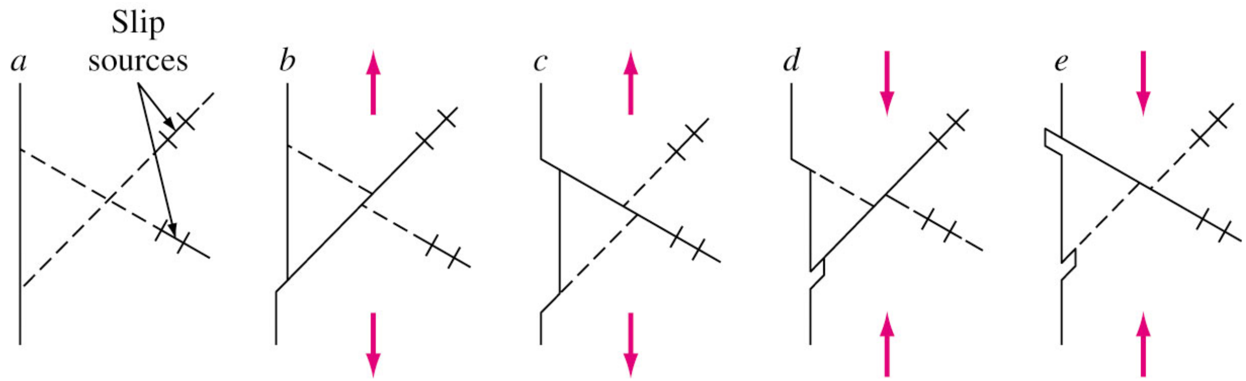


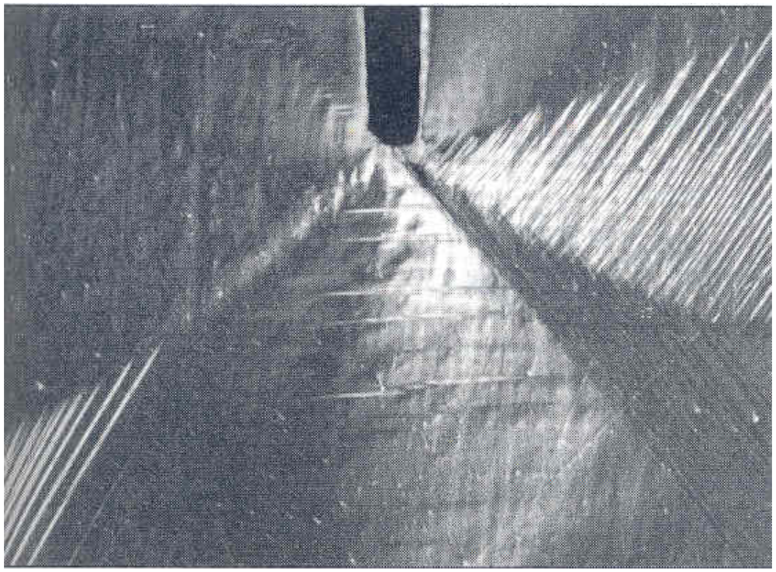
Fatique-fractures surface of steel shaft

Different types of stress cycles are possible: axial, torsional and flexural



Structural Changes in Fatigue Process





- Crack initiation first occurs

- Reversed directions of crack initiation caused surface ridges and groves extrusion and intrusion: first stage, very slow (0.1nm/cycle)

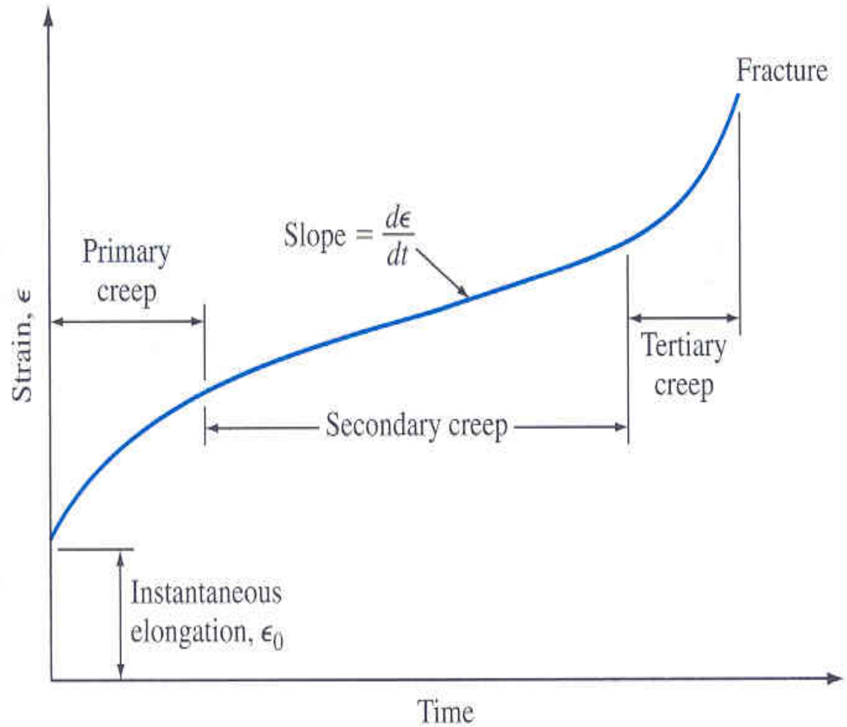
- Crack growth changes direction to be perpendicular to maximum tensile stress (rate few microns/sec)

- Sample rapture by ductile failure

7.3 Creep in Metals

Creep is **progressive plastic deformation** under constant stress with time
Important in high temperature applications

Primary creep: creep rate decreases with time due to strain hardening
Secondary creep: Creep rate is constant due to simultaneous strain hardening and recovery process
Tertiary creep: Creep rate increases with time leading to necking and fracture



Creep test:

- constant load (stress)
- different temperatures

Creep rate – $\Delta\varepsilon / \Delta t$

7.4 Larsen-Miller Parameters

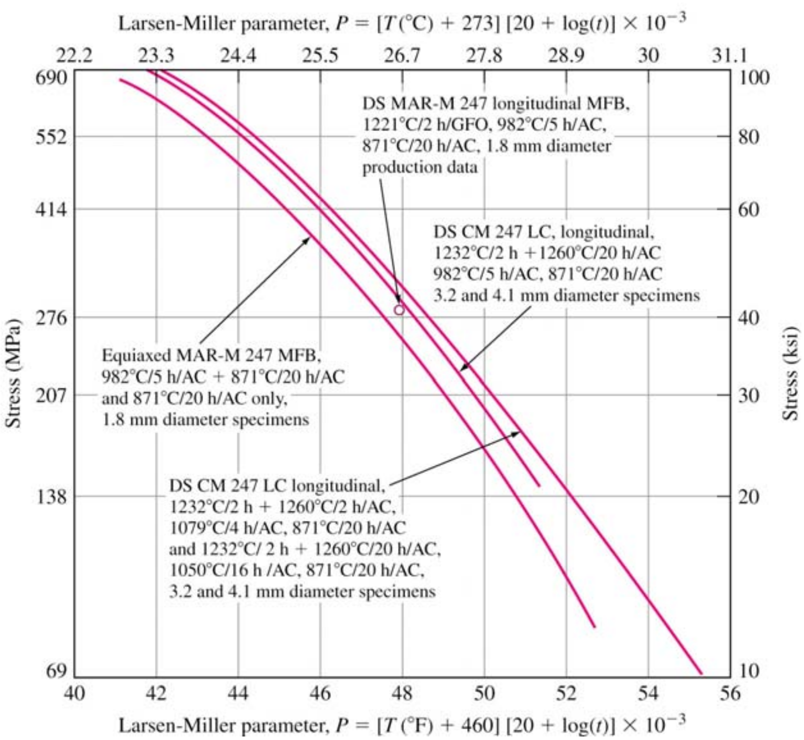
- *Larsen Miller parameter* is used to represent creep-stress rupture data

  P (Larsen-Miller) = T[log t_r + C]

  T - T(K), t_r = stress-rupture time, h; C - Constant (order of 20)

  or P (Larsen-Miller) = [T(^{0}C) + 273(20+log t_r)

  At a given stress level, the log time to stress rupture plus constant multiplied by temperature remains **constant** for a given material

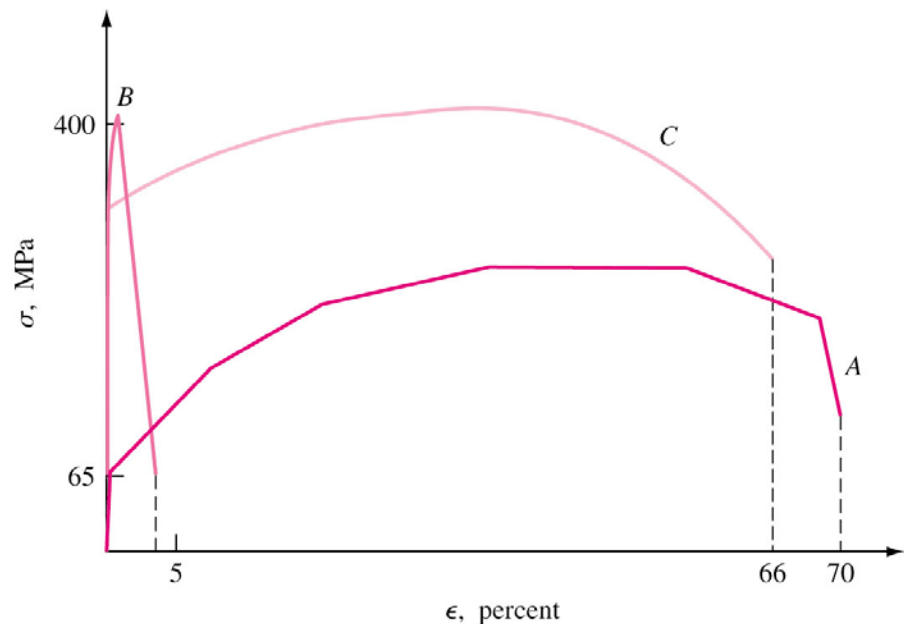


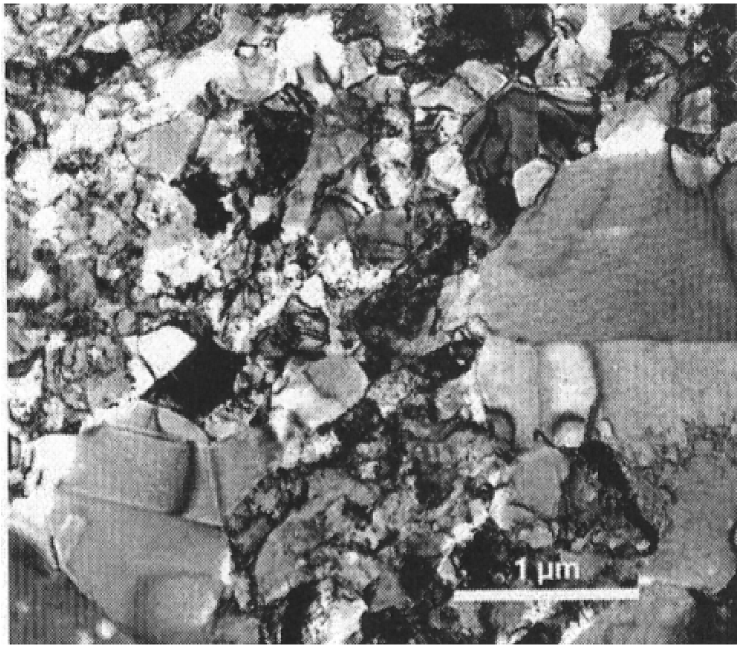
Q: Using the L.M. parameter plot at a stress of 207 MPa (30ksi), determine the time to stress-rupture at 980°C for directionally solidified alloy CM 247 (upper curve)

7.5 Ductility and Strength

Coarse grained – low strength, high ductility
Nanocrystalline – high strength, low ductility (because of failure due to shear bands)

Ductile nanocrystalline copper :
- Can be produced by old rolling at liquid nitrogen temperature
    - Additional cooling after each pass
    - Controlled annealing





- Fatigue crack growth is increased in the intermediate regime with decreasing grain size

Strengthening in Metals

- The ability of a metal to plastically deform depends on the ability of the dislocation to move
- Mechanical strength can be increased by hindering dislocation motion

- Methods for strengthening:

1. Make the grains smaller: misalignment between grains at the boundaries acts as a barrier
2. Make a solid state solution (alloy): impurity atoms introduce strain, minimum strain energy, if located at dislocation
3. Strain hardening: cycle stress many times, increase dislocation density, dislocations interfere with each other