Mechanical Properties

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Introduction

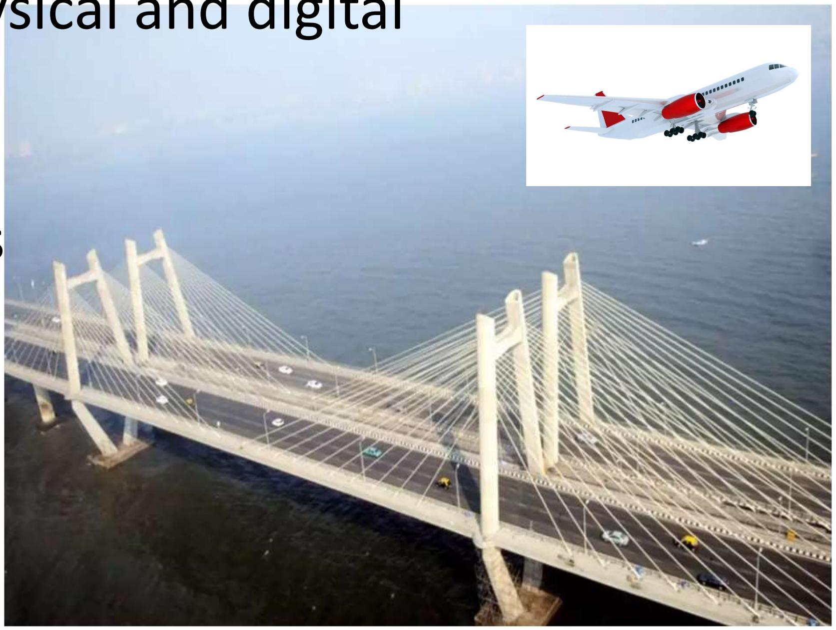
- Modern civilization based on physical and digital infrastructure

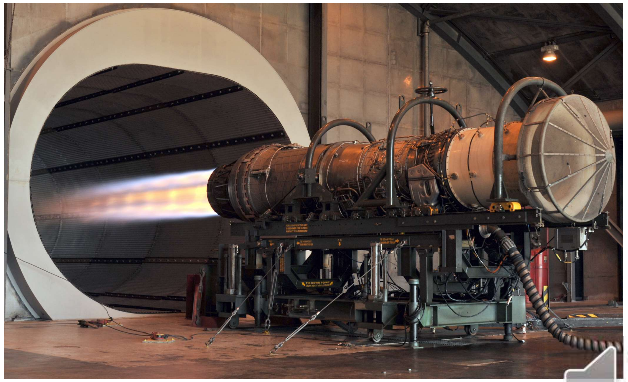
- Roads, railways, planes and ships for transport of materials and human

- Structural materials are very useful

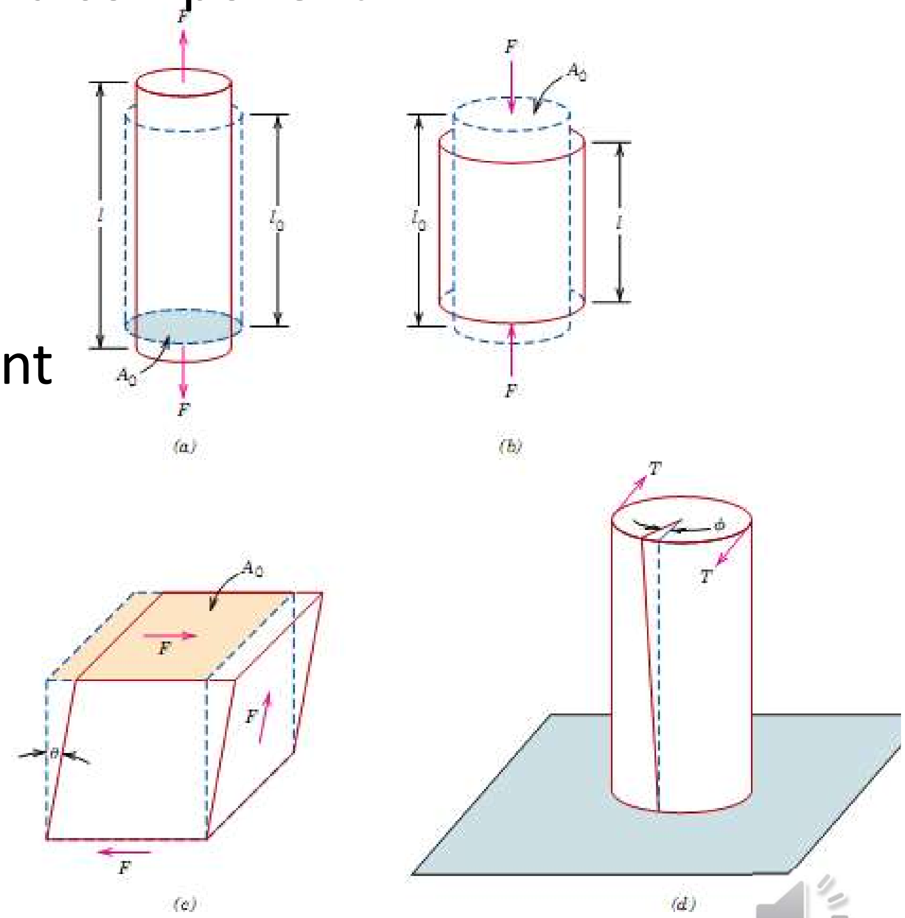
- Metal utensils, porcelain cutlery, plastic bottle in fridge

- Mechanical properties important





- Different materials different mechanical properties
- Structural materials bear load in a component
- Tensile, compressive, shear or torsional nature of forces
- Response of material is important



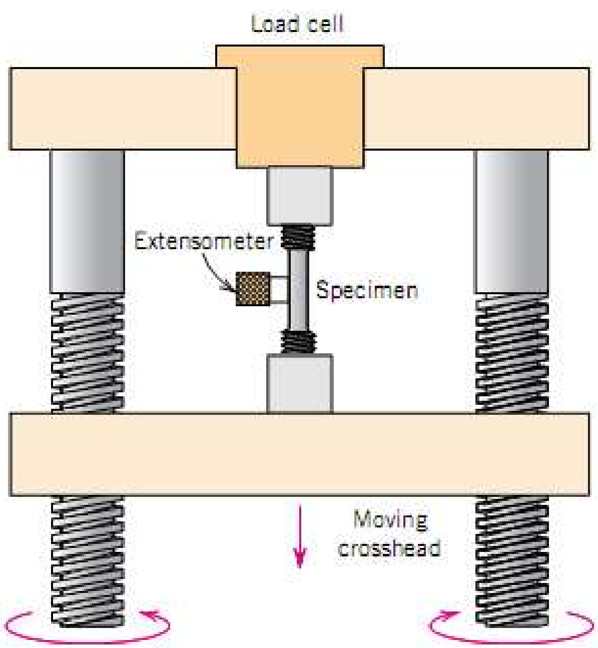
Tensile Properties

- Engineering Stress and Strain

s not $$\sigma = \frac{F}{A_0}$$

e not $$\epsilon = \frac{l_i - l_0}{l_0} = \frac{\Delta l}{l_0}$$

- ***F*** and ***l_i*** *are* <u>instantaneous force and length</u>*, respectively.*



Callister

Figure 6.2 A standard tensile specimen with circular cross section.

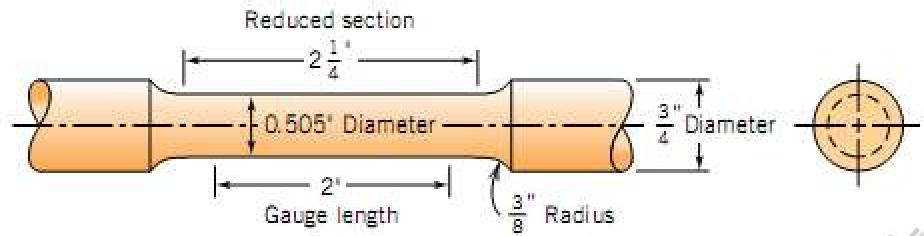
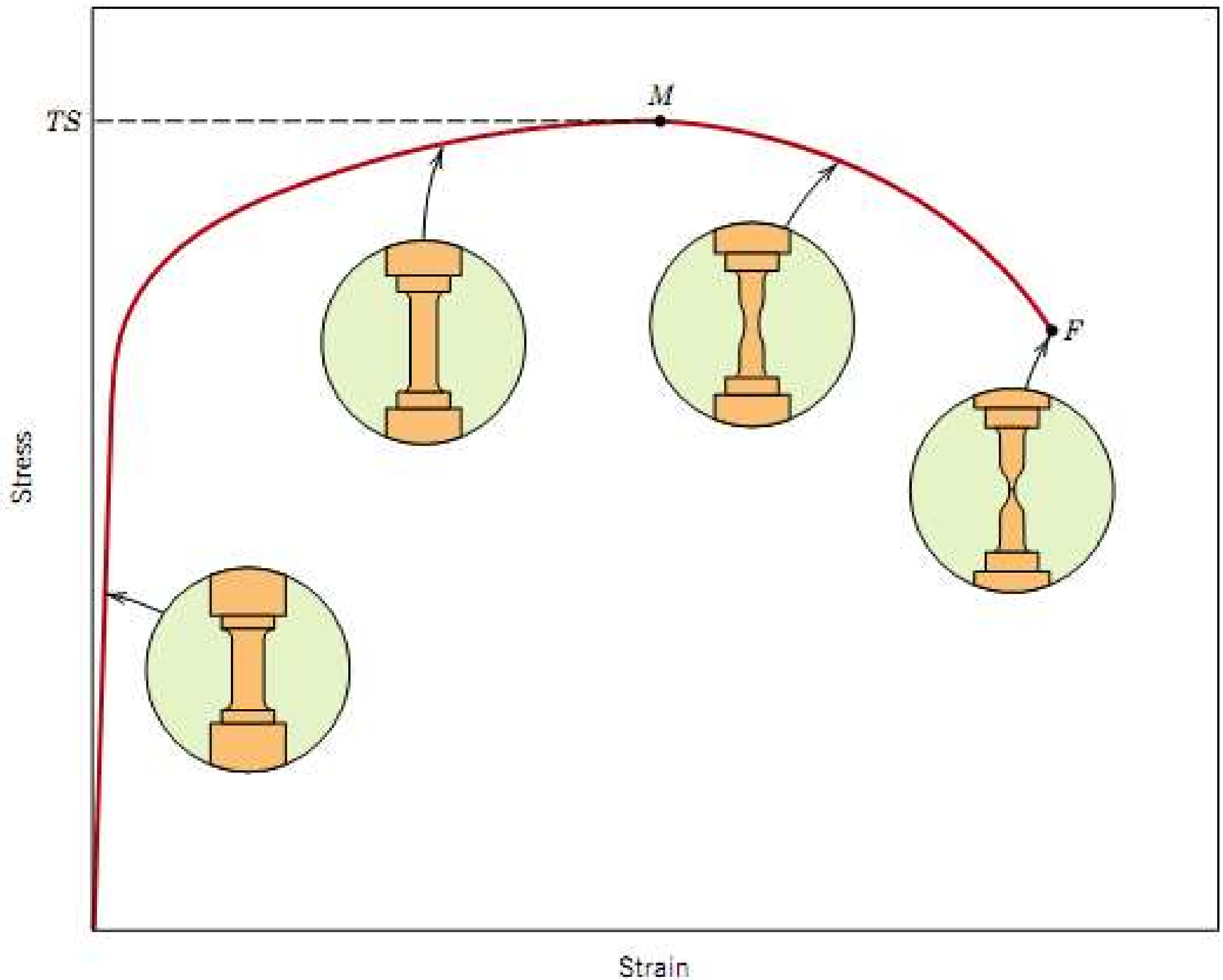
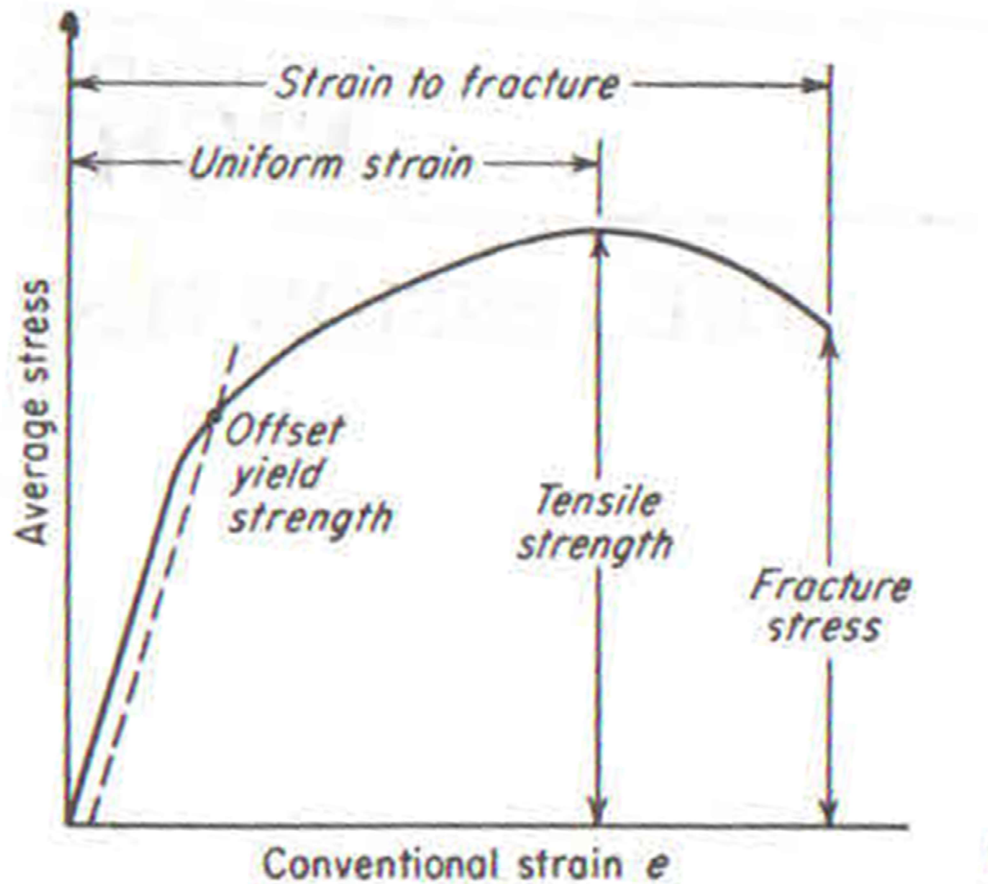


Figure 6.11 Typical engineering stress–strain behavior to fracture, point F. The tensile strength TS is indicated at point M. The circular insets represent the geometry of the deformed specimen at various points along the curve.





Dieter
Courtney,
Hertzberg

Elastic Limit and Yield Strength

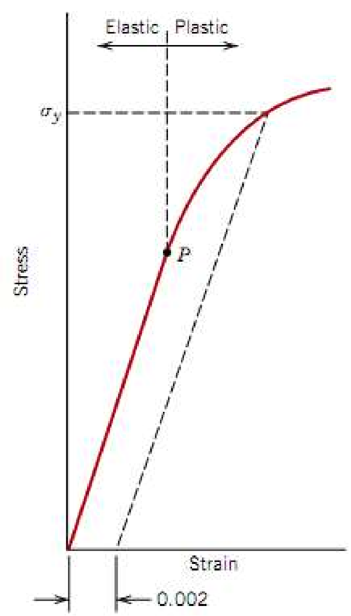
- True Elastic limit $\varepsilon \sim 10^{-6}$ $\longrightarrow$ Hooke's law is valid
- Proportional limit as the first departure from linearity
- Elastic limit as the stress that causes the first plastic deformation
- The more accurate the strain measurement is, the lower is the stress at which plastic deformation and nonlinearity can be detected
- Offset yield strength $\longrightarrow$ construct a straight line parallel to the initial linear portion of the stress–strain curve, but offset from it by e = 0.002 (0.2%.)

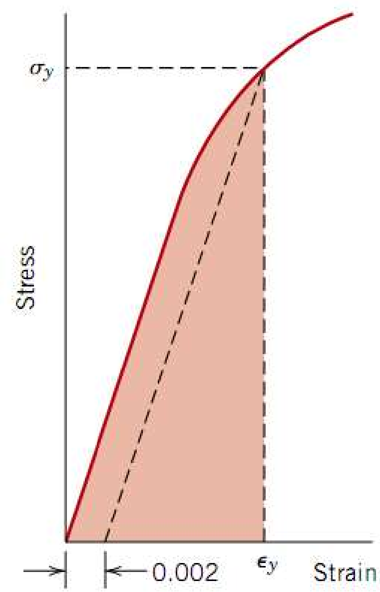
Proof stress and upper and lower yield point

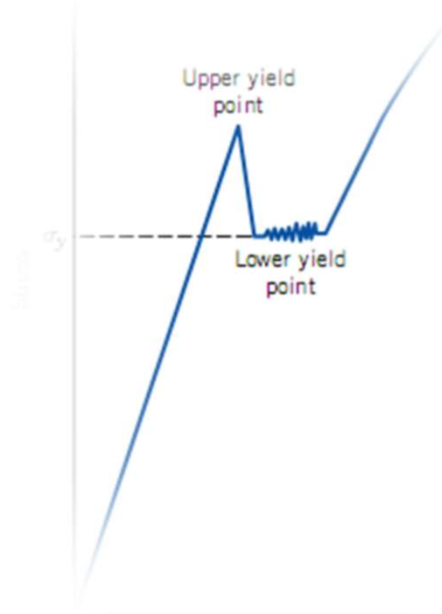
Continuous yielding

0.02% Proof stress or Yield stress

Upper and lower yield point in steel







True stress-True strain

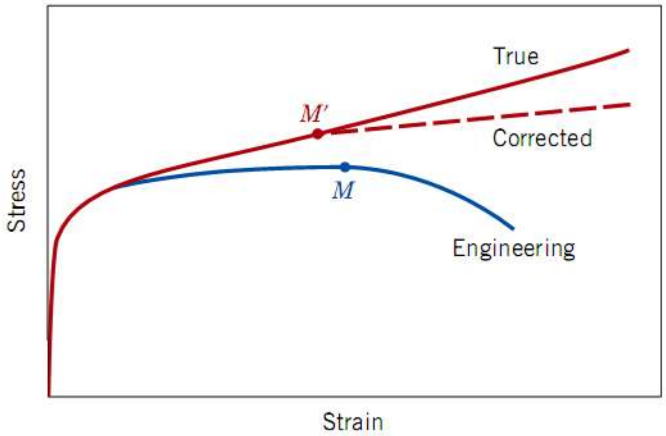
$$True\ stress = \sigma = \frac{P}{A} = \frac{P}{A_0}\frac{A_0}{A} = s(1+e)$$

$$A_0 L_0 = AL$$

$$e = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0}$$

$$\frac{L}{L_0} = \frac{A_0}{A} = 1 + e$$

$$\varepsilon = \ln(1+e)$$



Plastic deformation requires energy

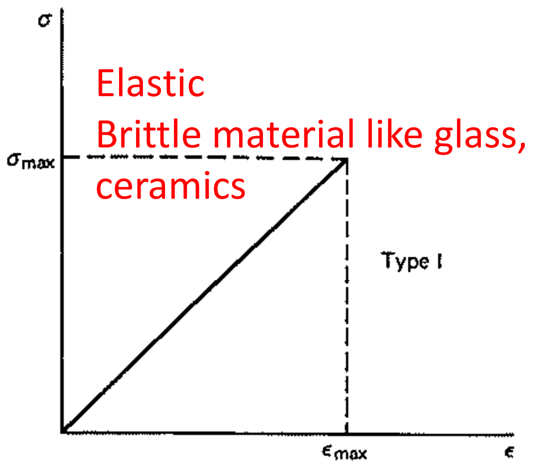
Stress increases with strain
Strain hardening

Necking starts when strain hardening is not able to compensate for decrease in load bearing capacity due to decrease in cross section area

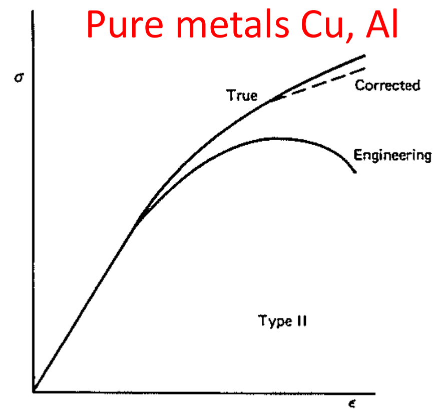
Where
s = engineering stress = P/A_0
e = engineering strain

Different type of stress-strain curve

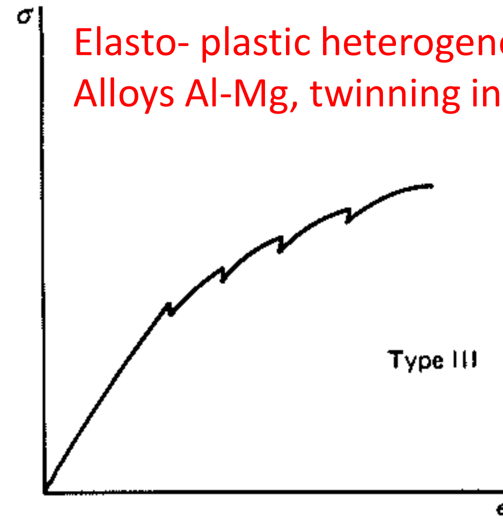
Elastic
Brittle material like glass, ceramics



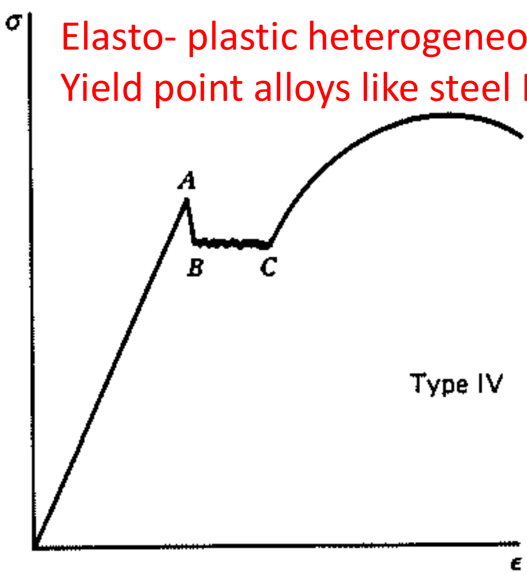
Elasto-plastic homogenous
Pure metals Cu, Al



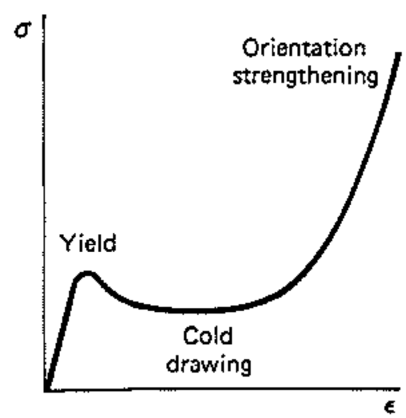
Elasto- plastic heterogeneous
Alloys Al-Mg, twinning in Ag



Elasto- plastic heterogeneous
Yield point alloys like steel Fe-C

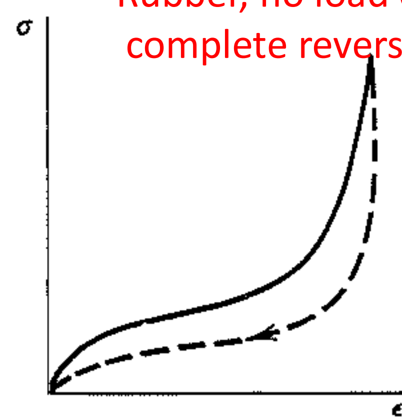


for crystalline polymer
Structure breakdown
and re-orientation



(a)

Rubber, no load drop
complete reversibility



(b)

Ductility

Ductility is defined as the degree of plastic deformation that has been sustained before fracture.

It is expresses as either

(a) Percent elongation

$$\%\mathrm{EL} = \left(\frac{l_f - l_0}{l_0}\right) \times 100$$

(b) Percent reduction in area

$$\%\mathrm{RA} = \left(\frac{A_0 - A_f}{A_0}\right) \times 100$$

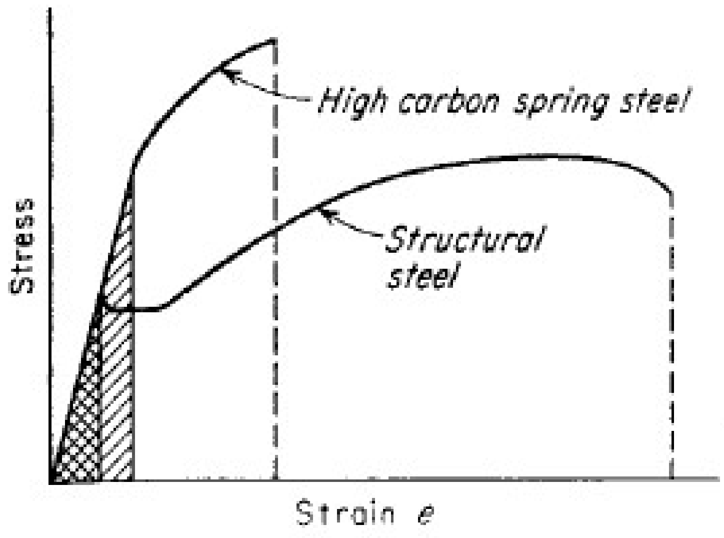
- *%EL depends on the l_0*
- A_f is cross-sectional area at the point of fracture

Ductility information is required when:

Forming a metal into a give shape, the ductility informs about the maximum strain it can bear before fracture.

Resilience

Resilience is the capacity of a material to absorb energy when it is deformed elastically and then, upon unloading, to have this energy recovered. The associated property is the *modulus of resilience*, U_r, which is the strain energy per unit volume required to stress a material from an unloaded state up to the point of yielding.



$$U_r = \int_0^{\epsilon_y} \sigma \, d\epsilon$$

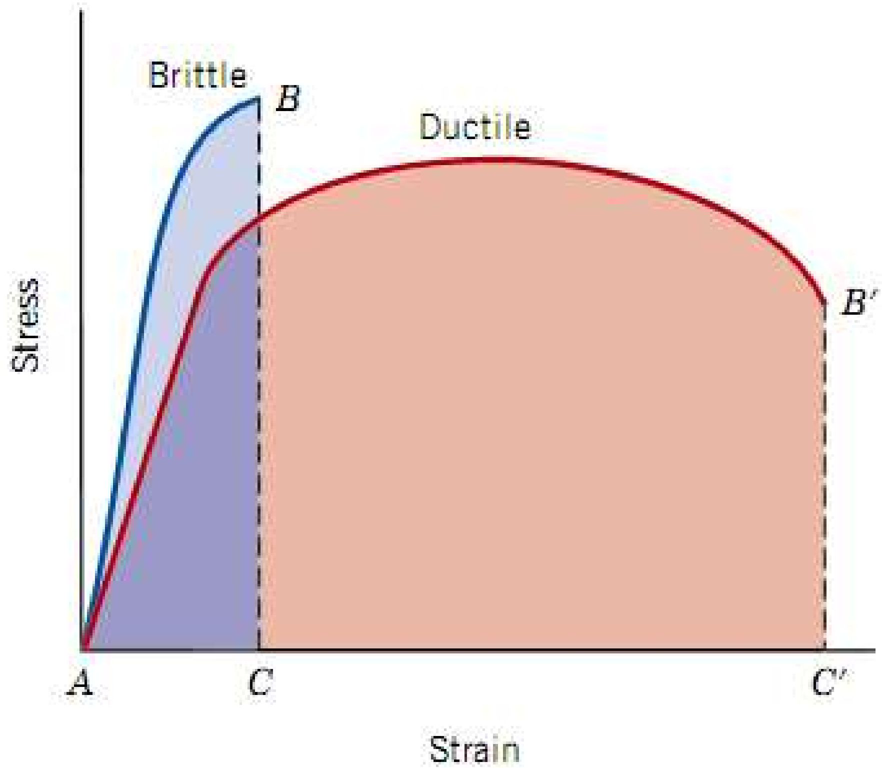
$$U_r = \tfrac{1}{2} \sigma_y \epsilon_y$$

$$U_r = \frac{1}{2}\sigma_y \epsilon_y = \frac{1}{2}\sigma_y\left(\frac{\sigma_y}{E}\right) = \frac{\sigma_y^2}{2E}$$

Thus, resilient materials are those having high yield strengths and low moduli of elasticity; such alloys would be used in spring applications.

Toughness

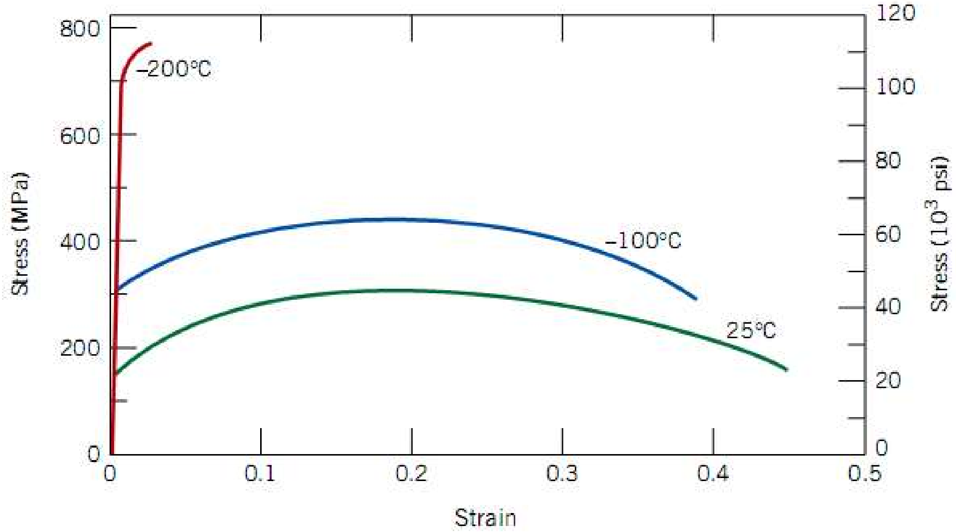
Static toughness: It is the extent of energy absorbed before fracture It is the area under the stress-strain *curve up to the point of fracture.*

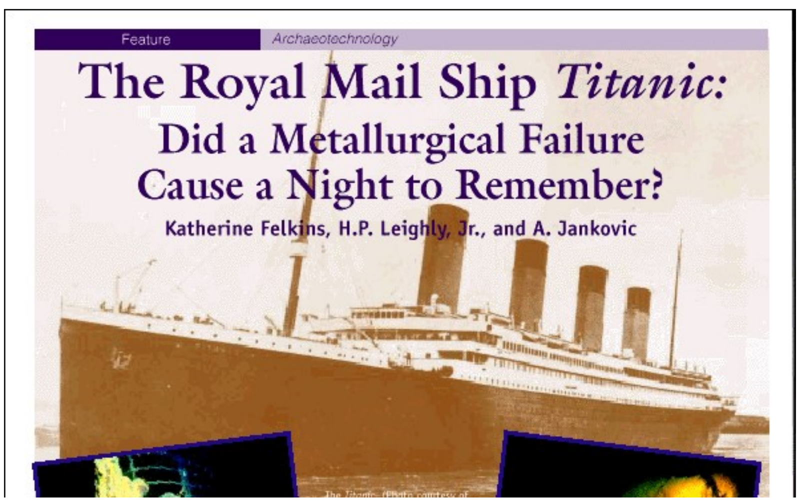


Strain rate and temperature effect on tensile properties

Ductile to brittle transition temperature

Less energy absorbed

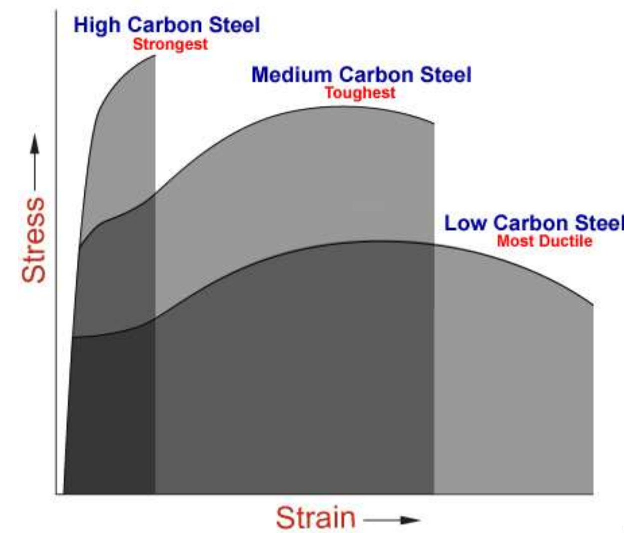



Feature Archaeotechnology

The Royal Mail Ship *Titanic:*

Did a Metallurgical Failure Cause a Night to Remember?

Katherine Felkins, H.P. Leighly, Jr., and A. Jankovic



Ductile and Brittle fracture

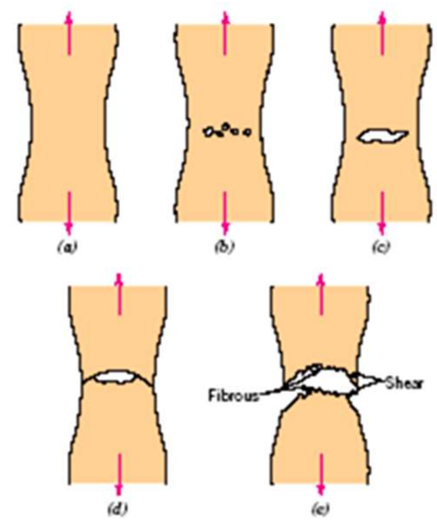
Void nucleation, growth and coalescence in DF

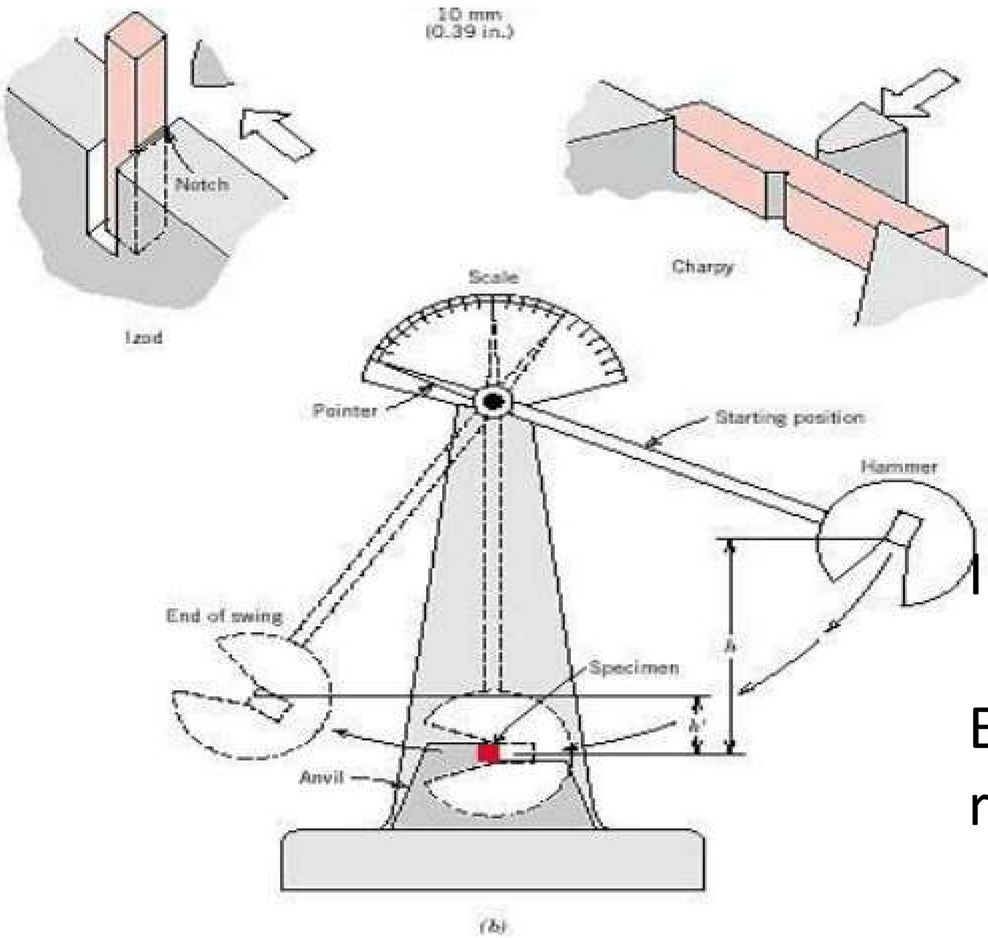
Crack growth and failure in BF

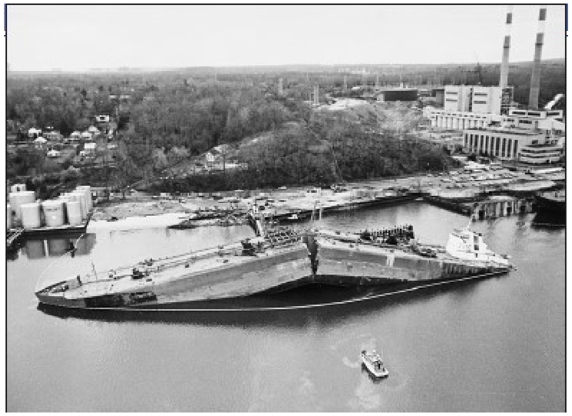
Inter and trans granular

Fibrous and cleavage

Charpy impact test







https://www.researchgate.net/figure/Apparatus-for-Charpy-Impact-Testing-of-Materials-Callister-2009_fig3_290436477

Impact test

Energy absorbed at high strain rate

Mechanistic way of describing fracture is in terms of fracture toughness

Hardness

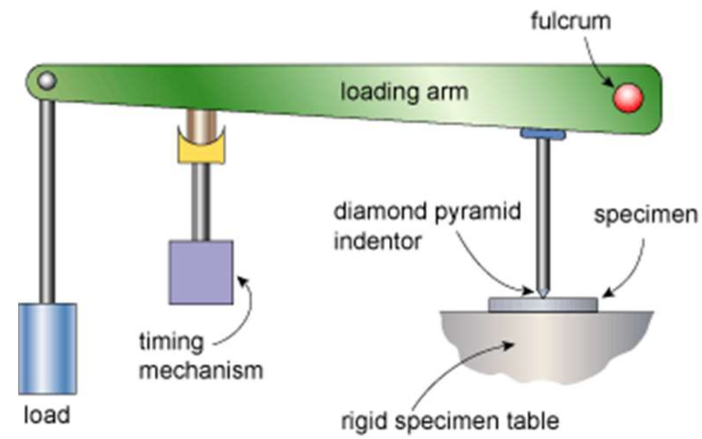
Resistance to plastic deformation

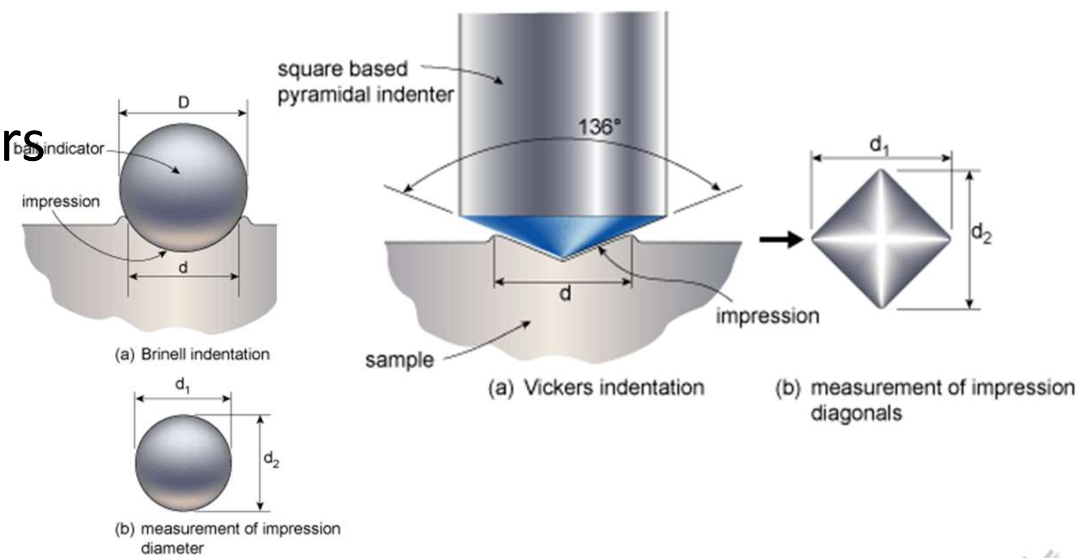
Lpcalised plastic deformation

Macro-micro-nano indentation

Instrumented indentation

Different shape of indenters





Plastic deformation and dislocation motion

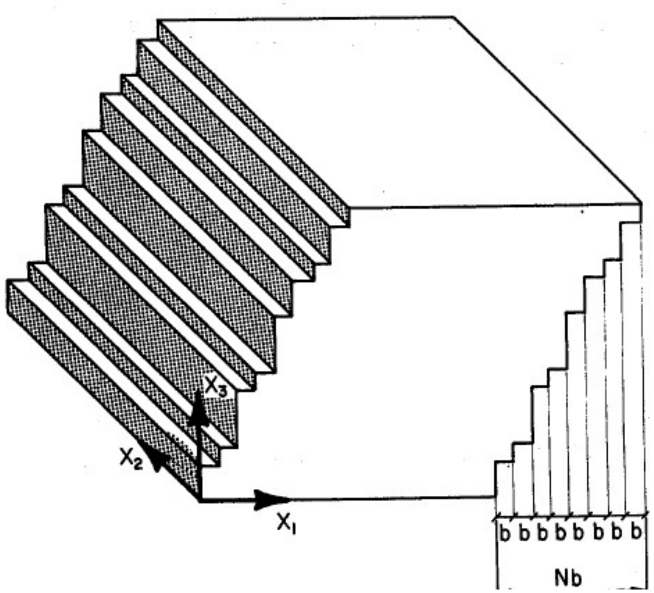
Elastic deformation in stretching of bonds and bonds break locally in plastic deformation

Large scale motion of dislocation marks plastic deformation

Avalanche mechanism

Strain rate decides velocity of dislocations

Accommodation of strain by slip



$$\gamma_{13} = Nb / dx_3$$

$$\rho = Ndx_2 / dx_1 * dx_2 * dx_3$$

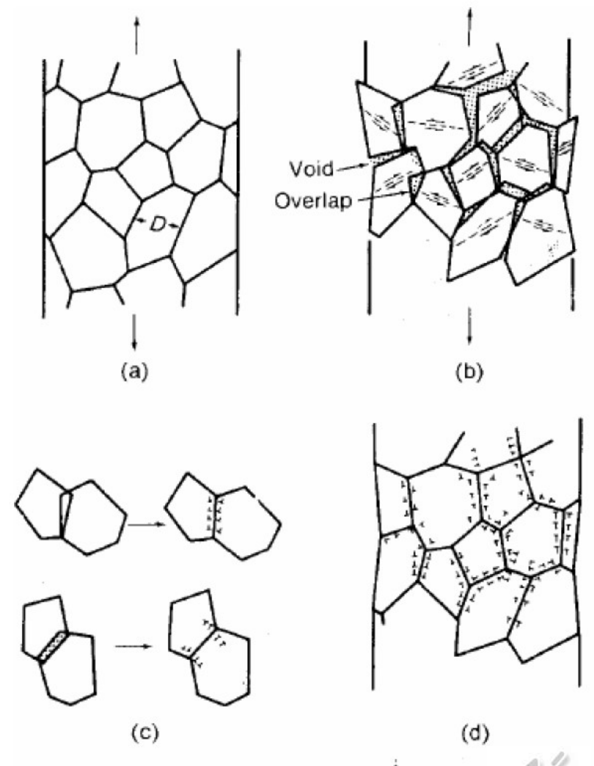
$$\gamma_{13} = \rho b dx_1$$

$$\gamma_p = \rho b \bar{l}$$

$$\dot{\gamma}_p = \rho b v$$

Ashby's model

- Statistically stored dislocations (SSD) → Incidental dislocation boundar (IDB)
- Geometrically necessary dislocations (GND) → Geometrically Necessary Boundaries (GNB)
- GND required to maintain strain compatibility
- SSD formed by random traping of dislocations
- SSD proportional to strain
- GND proportional to strain and gradient of strain



- Plastic deformation → dislocations

- Interaction of dislocations with each other and other defects can be exploited to achieve strengthening

- Engineering material properties using chemical (alloying), thermal (heat treatment) and mechanical (forming) processes

- Strength ↑ Ductility ↓

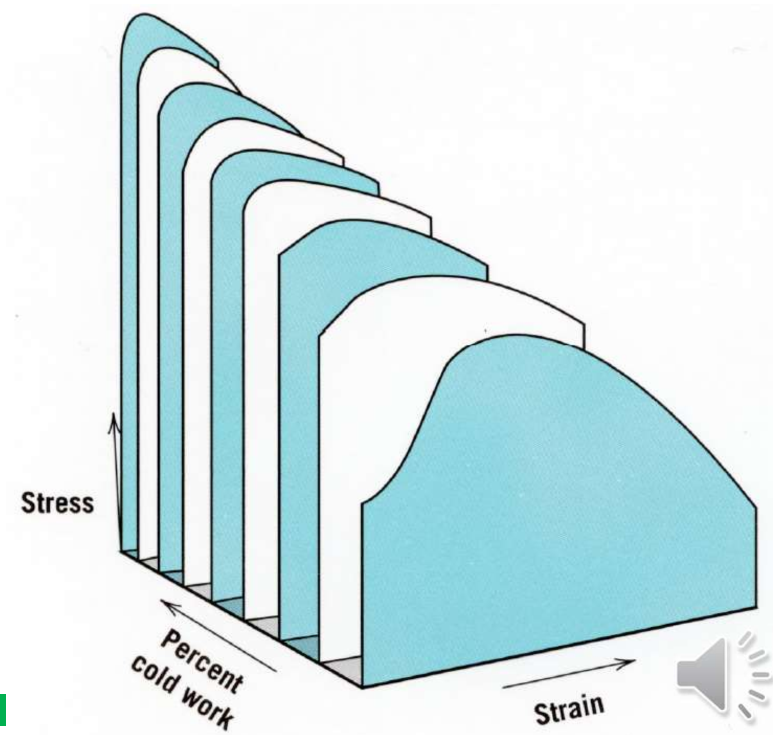
- **Strength Ductility paradox**

- High strength and sufficient ductility is still the holy grail for materials engineers

- Dislocation motion is hindered by
  - Other dislocations (strain hardening)
  - Grain boundaries (Hall-Petch hardening)
  - Solute and interstitial atoms (solid solution hardening)
  - Precipitates (precipitation hardening)
  - Dispersoids (dispersion hardening)

$$\tau = \tau_0 + \alpha \overline{M} G b \sqrt{\rho}$$

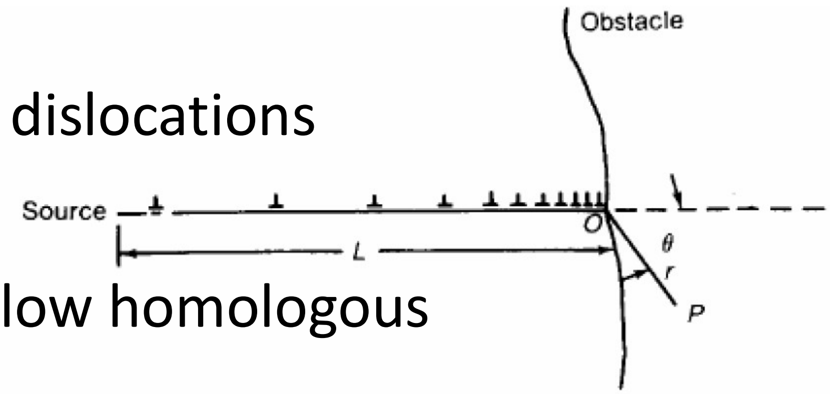
Strain hardening



- Dislocation-dislocation interaction
- Forest of dislocations
- Increase in DD with strain
- Impedes further dislocation movement
  but provides strain hardening

Grain size strengthening

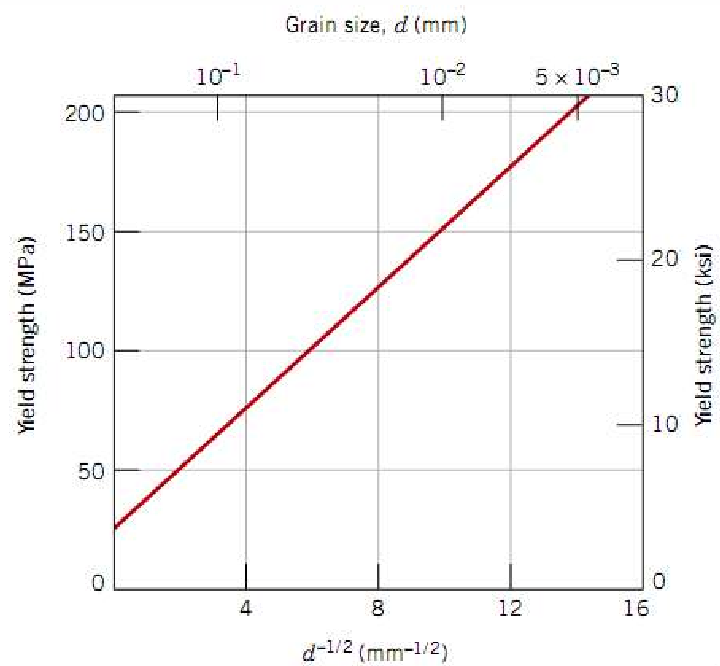
- Grain boundaries act as barrier for dislocations



- Gb stronger than grain interiors at low homologous temperature (T/T_m)

- Pile up dislocations

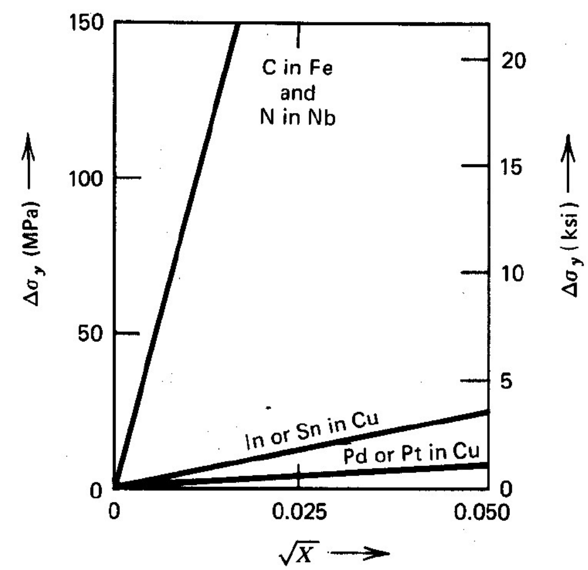
$$\sigma_y = \sigma_0 + k_y d^{-1/2}$$



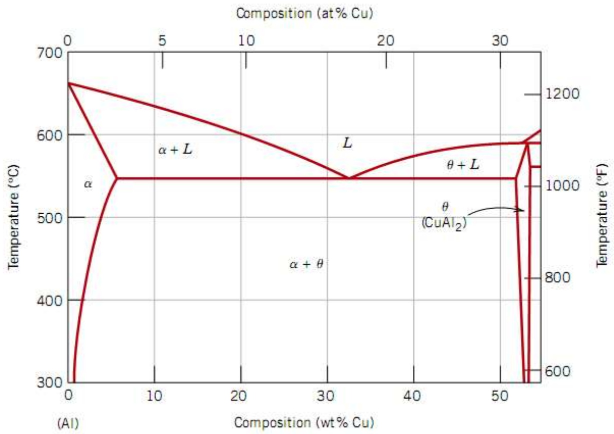
Effect of grain size on YS of ferrite from R. A. Grange, ASM Trans. 59 (1966)

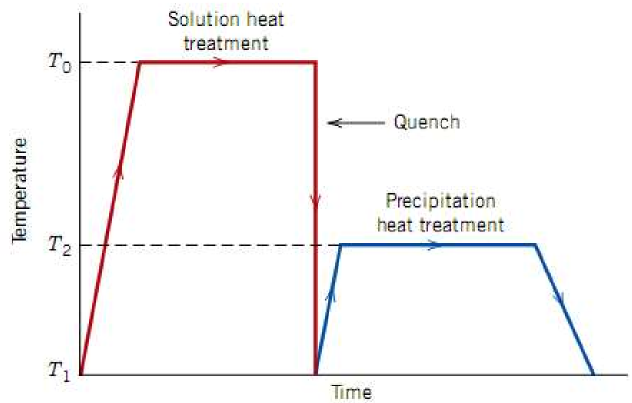
Solid solution strengthening

- Elastic interaction between dislocation and solute atoms
- Size of solute atom and dislocation stress field very important
- Remember edge has sigma and tau terms in stress tensor therefore presence of shear and hydrostatic stress and distortion and dilatation.Only the latter for screw
- Solution formation when a foreign atom substitutes existing atom or sits at an interstitial position



Precipitation hardening





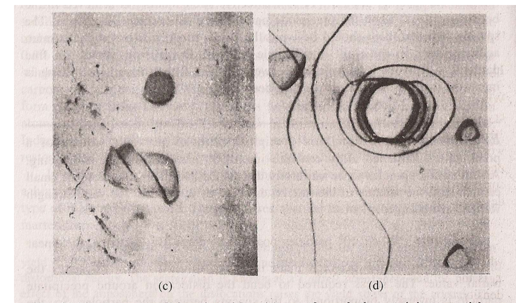
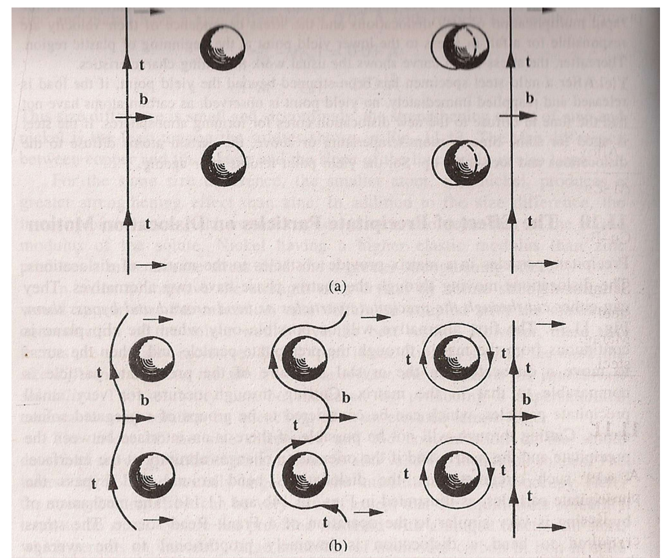
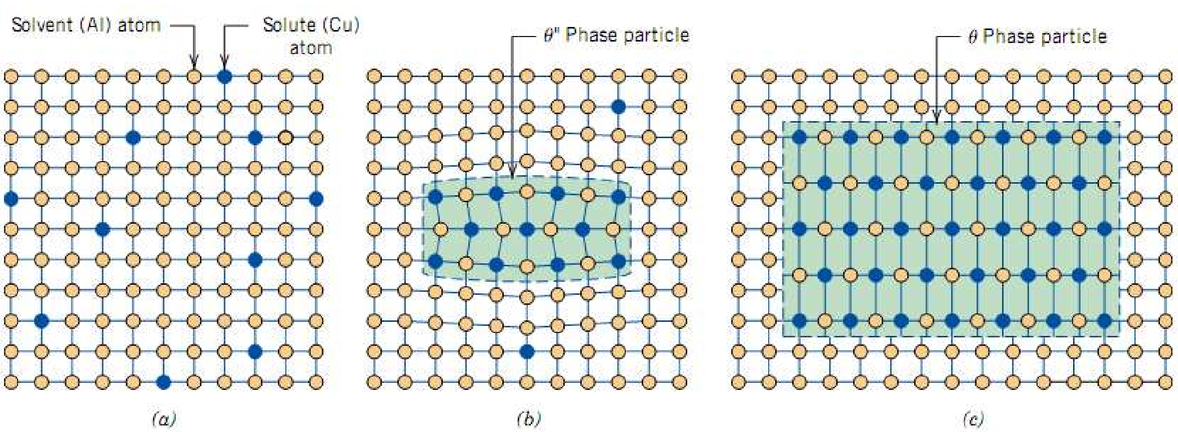


Fig. 11.14 A moving dislocation either (a) cuts through the precipitate particles or (b) bypasses them. Electron micrographs depicting these two processes are shown in (c) and (d). [(c) and (d) *Courtesy:* F.J. Humphreys and V. Ramaswamy.]

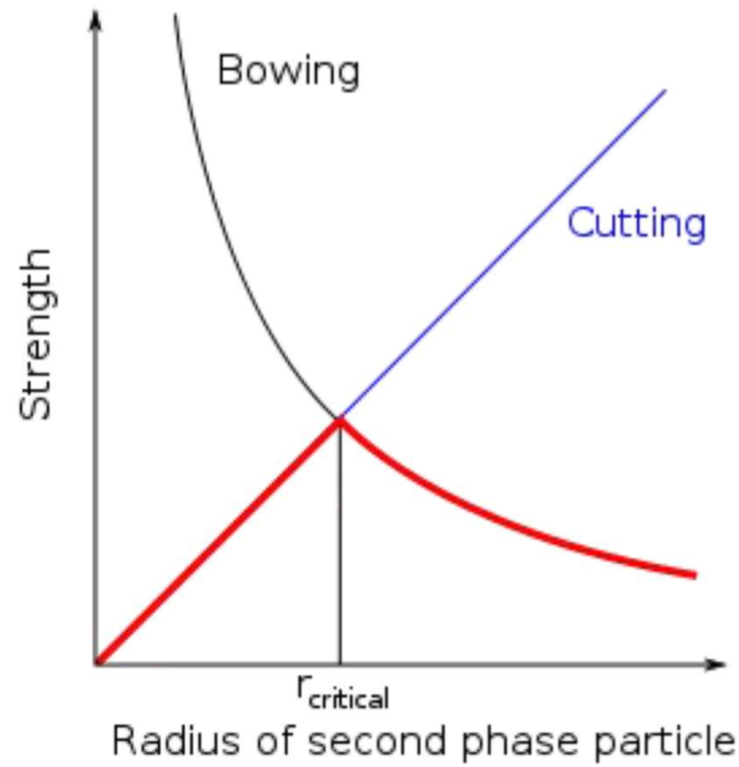




Precipitation hardening

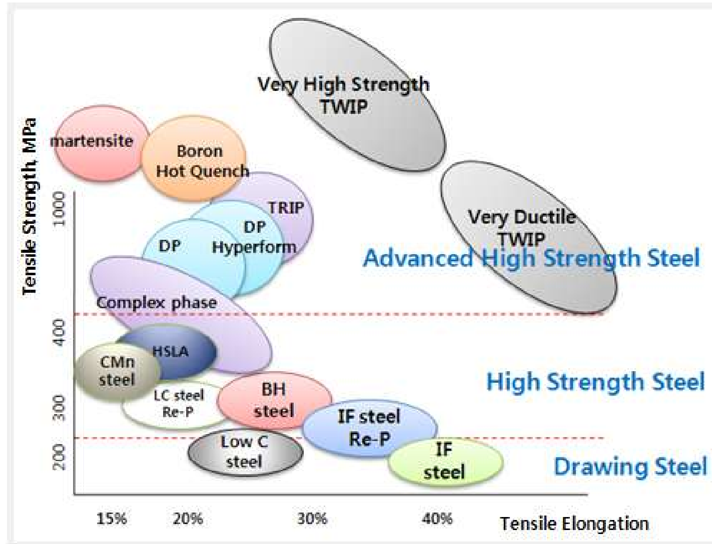
$$\Delta\tau_{cutting} \propto r$$

$$\Delta\tau_{bowing} \propto \frac{1}{r}$$



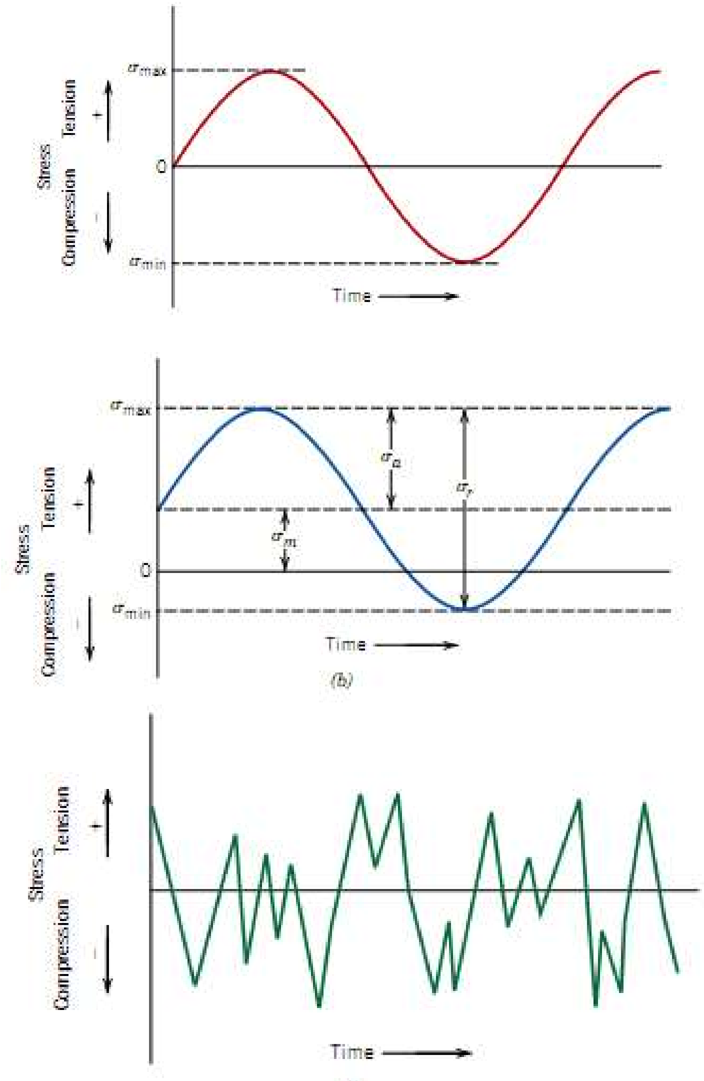
Strengthening in steels

- FCC to BCT transformation
- Difficult slip in martensite phase
- Barrier to dislocations
- Bainitic strengthening
- TWIP and TRIP steels



- Twinning Induced Plasticity and Transformation Induced Plasticity
- High strength with sufficient ductility
- Multi-phase steels
- Nano-pearlite 8 GPa yield strength

Fatigue



σ_{max}
O
σ_{min}
Stress
Tension
Compression
+
−
Time
σ_a
σ_r
σ_m
(b)

Mean stress for cyclic loading—dependence on maximum and minimum stress levels

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2}$$

range of stress for cyclic loading

$$\sigma_r = \sigma_{\max} - \sigma_{\min}$$

stress amplitude for cyclic loading

$$\sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{\max} - \sigma_{\min}}{2}$$

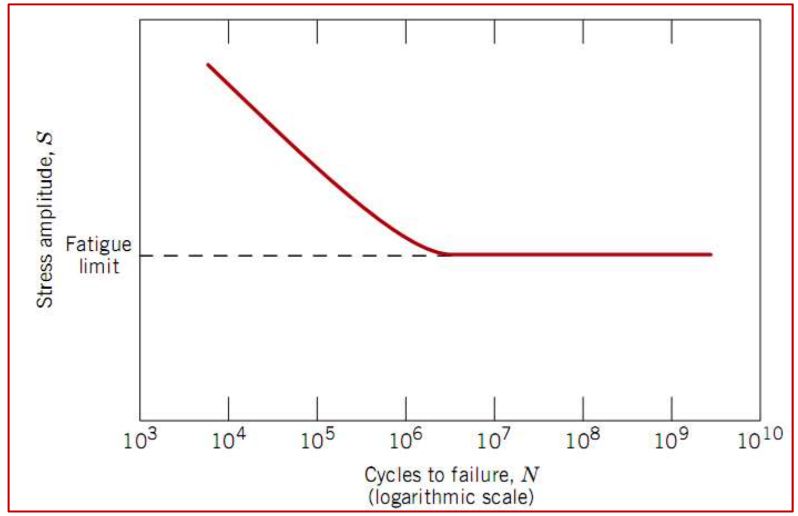
stress ratio

$$R = \frac{\sigma_{\min}}{\sigma_{\max}}$$

Fatigue limit or Endurance limit

Infinite life

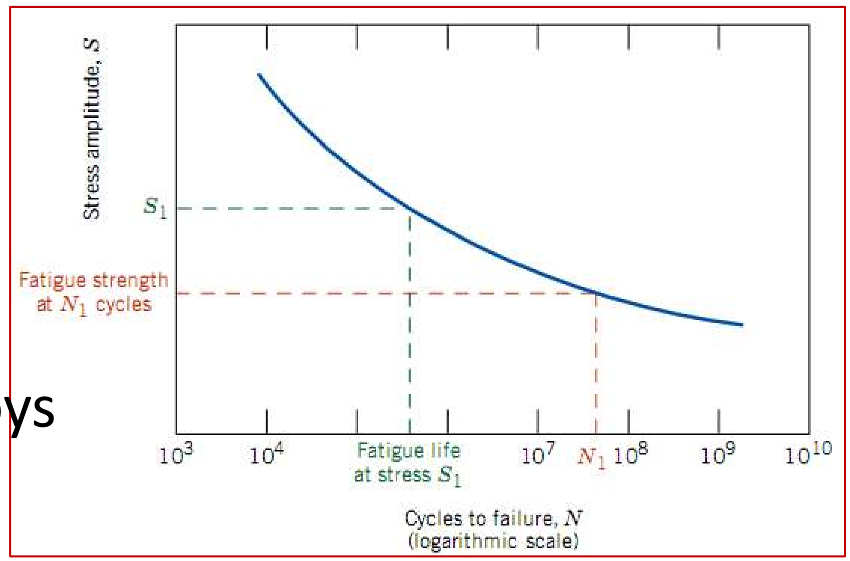
Titanium and steels

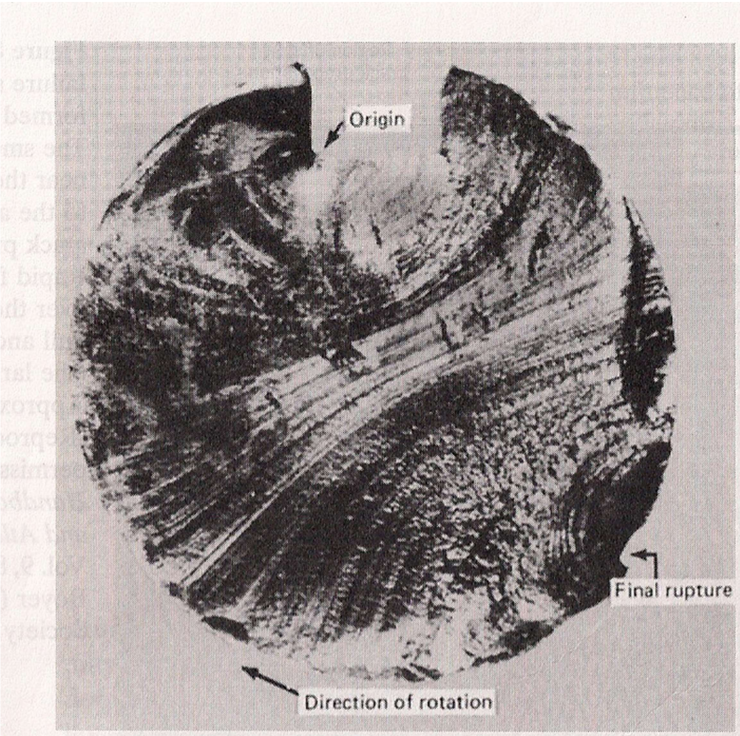


Fatigue strength

10^7 cycles

Aluminium and non ferrous alloys





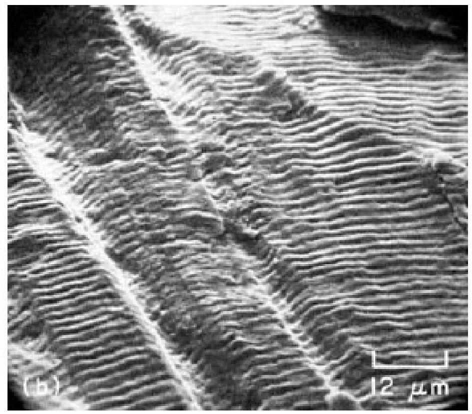


Figure 17.2. SEM picture of fatigue striations on a fracture surface of type 304 stainless steel. From *Metals Handbook*, Vol. 9, eighth ed., ASM, 1974.

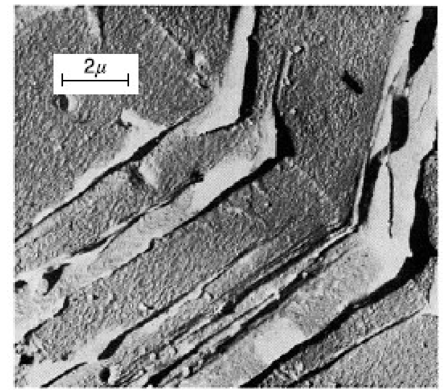


Figure 17.3. Intrusions and extrusions at surface formed by cyclic deformation. These correspond to persistent slip bands beneath the surface. From A. Cottrell and D. Hull, *Proc. Roy. Soc. (London)* Vol. A242 (1957).

Beach marks, striations, intrusions and extrusions

Forward and backward slip

Crack formation at surface and propagation to failure

90% engineering failures

Surface Effects

For many common loading situations, the maximum stress within a component or structure occurs at its surface. Consequently, most cracks leading to fatigue failure originate at surface positions, specifically at stress amplification sites. Therefore, it has been observed that fatigue life is especially sensitive to the condition and configuration of the component surface. Numerous factors influence fatigue resistance,

Design Factors

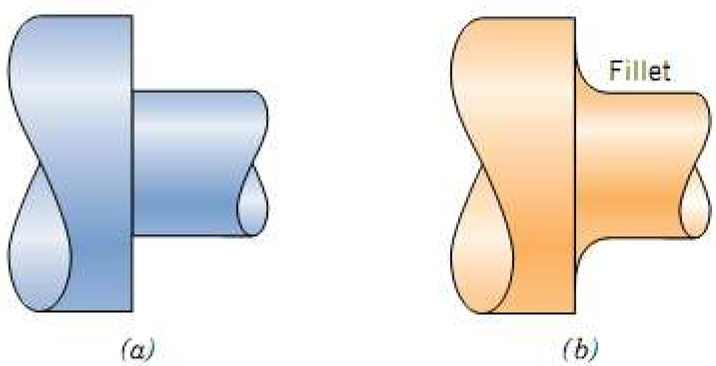


Figure 8.25 Demonstration of how design can reduce stress amplification. (*a*) Poor design: sharp corner. (*b*) Good design: fatigue lifetime improved by incorporating rounded fillet into a rotating shaft at the point where there is a change in diameter.

Surface Treatments

Surface polishing

During machining operations, small scratches and grooves are invariably introduced into the workpiece surface by cutting tool action. These surface markings can limit the fatigue life. It has been observed that improving the surface finish by polishing will enhance fatigue life significantly.

Introducing compressing stress on the surface

Residual compressive stresses are commonly introduced into ductile metals mechanically by localized plastic deformation within the outer surface region. Commercially, this is often accomplished by a process termed *shot peening*.

Creep

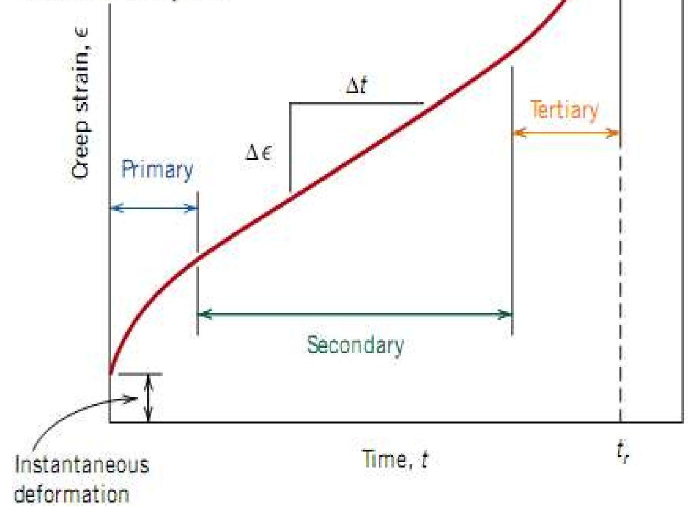
Creep is time-dependent plastic deformation, which is usually significant only at high temperatures, above recrystallization temperature (~0.3-0.5 T_m)

These flow processes occur due to the movement of point defects (vacancies) or dislocations under static loading

For metallic materials most creep tests are conducted in uniaxial tension using a specimen having the same geometry as for tensile tests

Constant load/stress

Figure 8.28 Typical creep curve of strain versus time at constant load and constant elevated temperature. The minimum creep rate $\Delta\epsilon/\Delta t$ is the slope of the linear segment in the secondary region. Rupture lifetime t_r is the total time to rupture.

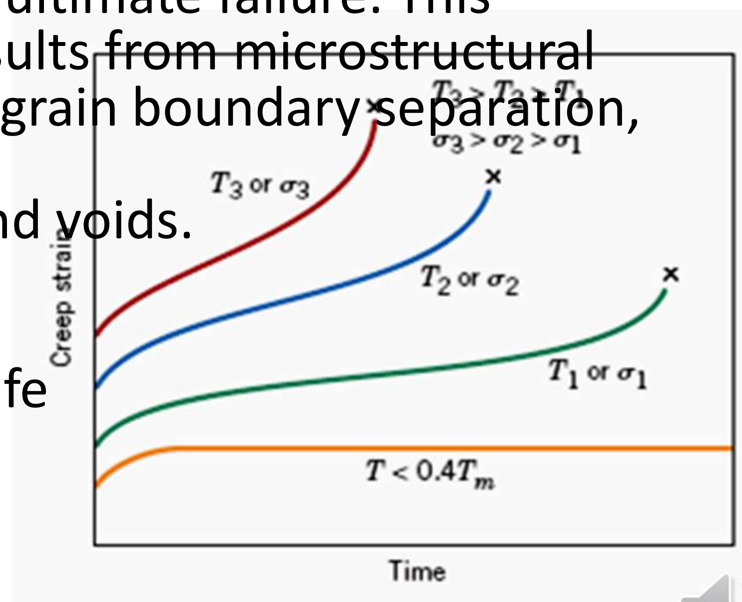


Primary or transient creep Continuously decreasing creep rate. Increase in creep resistance or strain hardening

Secondary or steady-state creep, Constant creep rate is constant. Balance between the competing processes of strain hardening and recovery, recovery being the process whereby a material becomes softer and retains its ability to experience deformation.

Tertiary creep, Acceleration of the rate and ultimate failure. This failure is frequently termed rupture and results from microstructural and/or metallurgical changes; for example, grain boundary separation, and
the formation of internal cracks, cavities, and voids.

Increase in temperature and load increases steady state creep rate and reduces creep life



Creep Mechanisms

- Several theoretical mechanisms have been proposed to explain the creep behavior for various materials;
  (i) stress-induced vacancy diffusion,
  (ii) grain boundary diffusion,
  (iii) dislocation motion, and
  (iv) grain boundary sliding.

- Each leads to a different value of the stress exponent *n* in the creep Equation.

- In addition, correlations have been made between the activation energy for creep Q_c and the activation energy for diffusion, Q_d.

$$\dot{\varepsilon}_s = K \quad \sigma^n \exp\left(-\frac{Q_d}{RT}\right)$$

$$\dot{\varepsilon} \quad = A \quad D \quad \frac{Gb}{kT}\left(\frac{b}{d}\right)^p \left(\frac{\sigma}{G}\right)^n$$

Creep Mechanisms

- Creep data of this nature are represented pictorially for some well-studied systems in the form of stress–temperature diagrams, which are termed *deformation mechanism maps*.

- These maps indicate stress–temperature regimes (or areas) over which various mechanisms operate.

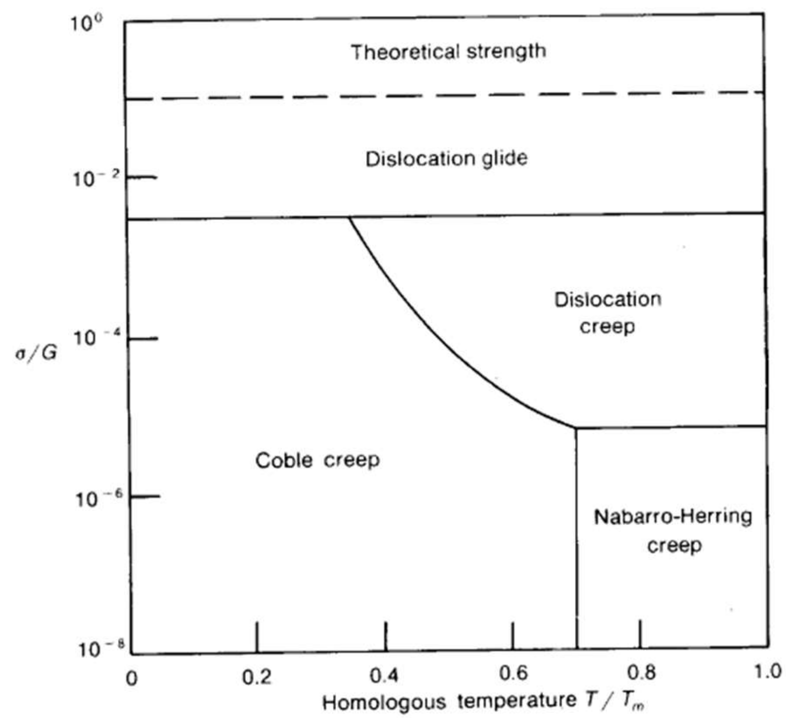


Figure 13-11 Simplified deformation mechanism map. (*After Ashby.*)

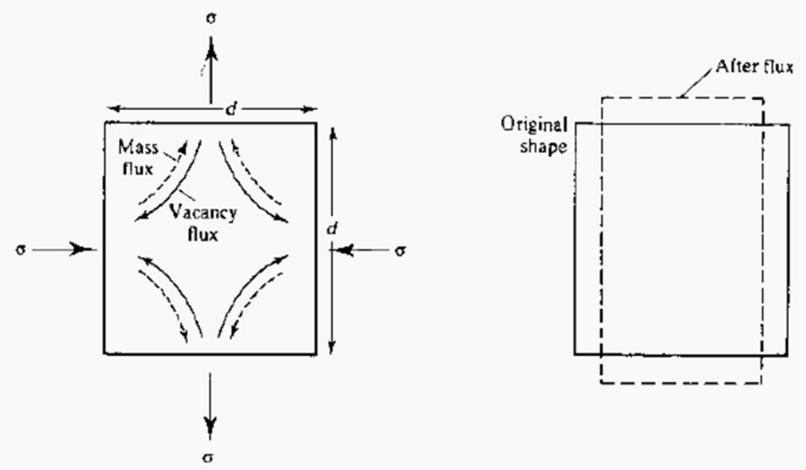


FIGURE 15.21 Schematic illustration of bulk diffusion. [From Courtney (1990) with permission from McGraw-Hill.]

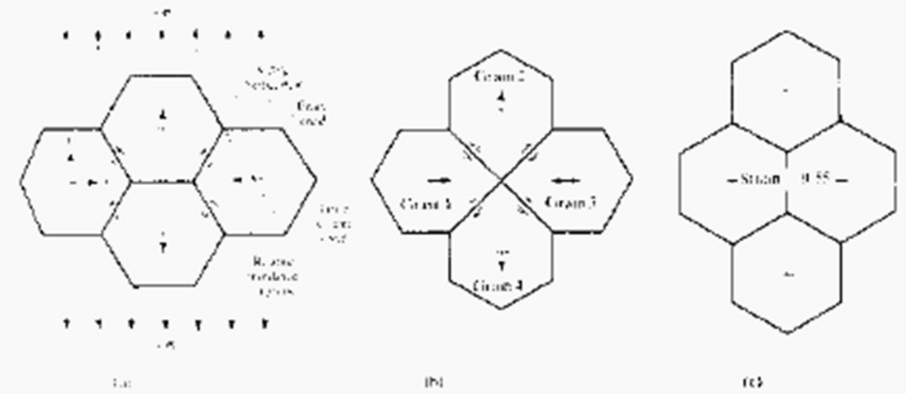


FIGURE 15.41 Grain switching mechanism of Ashby and Verrall: (a) initial state; (b) intermediate state; (c) final state. [From Ashby and Verall, 1973.]

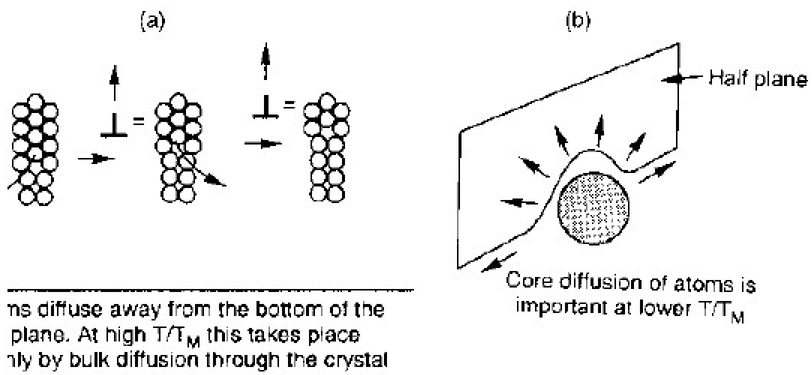


FIGURE 15.19 How diffusion leads to dislocation climb: (a) atoms diffuse from the bottom of the half-plane; (b) core diffusion of atoms. [From Ashby and Jones (1996) with permission from Butterworth-Heinemann.]

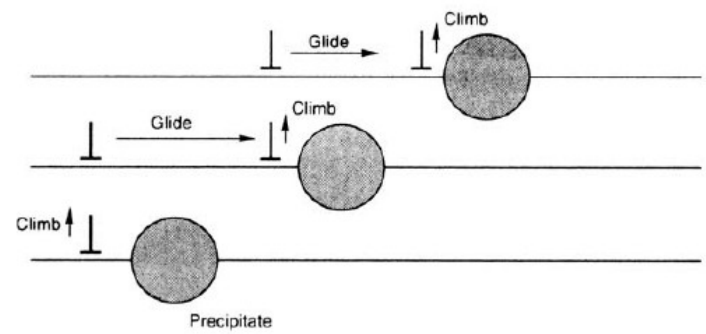


FIGURE 15.20 Schematic illustration of dislocation glide and climb processes. [From Ashby and Jones (1996) with permission from Butterworth-Heinemann.]

Superplasticity

- Exploit high temperature deformation for materials processing
- Maximum strain as high as few thousand percentage for metals
- Enhanced ductility for ceramics at high temp.
- Conditions for superplasticity
    - High strain rate sensitivity (m>=0.5)
    - Smaller grain size
    - High temperature
- Generally occurs at very slow strain rate
- It is imp to get superplastic behaviour at higher strain rate for industrial application

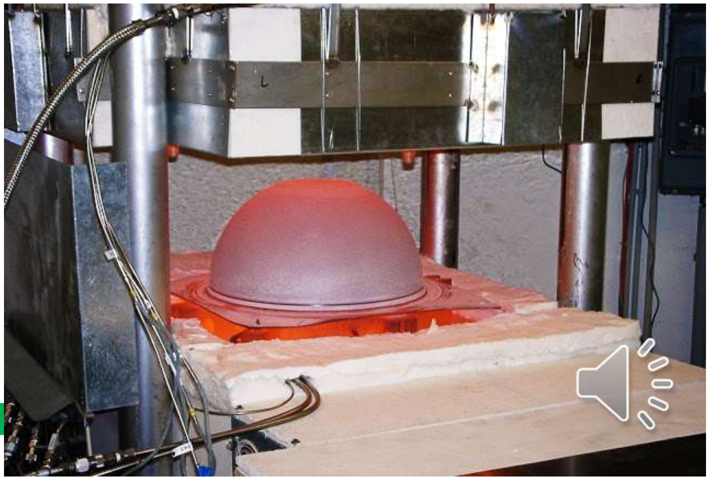
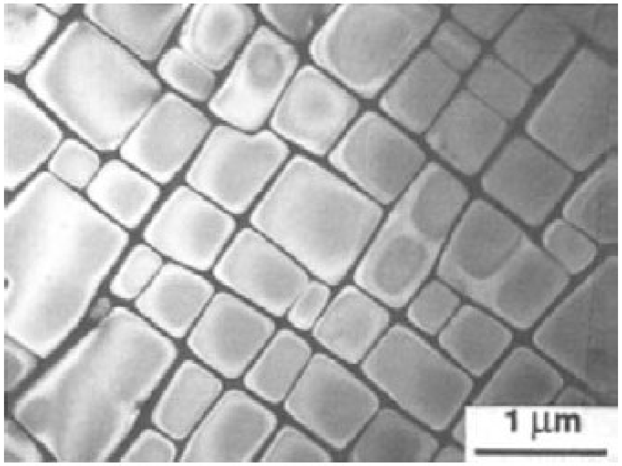


Image shows a metallic tank been blown from bottom by air (bottom Fig.) much like the girl blows her chewing gum)

Superalloys

- Based on nickel, titanium or aluminium
- Ordered Ni_3Al, NiAl and Ni matrix
- Fraction of precipitates is 70%
- Difficult for dislocations to move in ordered Ni3Al matrix
- Coherent interface
- Single crystal better than columnar grain structure which is better than equiaxed grains
- Excellent high temperature stability and oxidation resistance



Historical Development of Blade Design