Department of Civil Engineering
IIT Madras

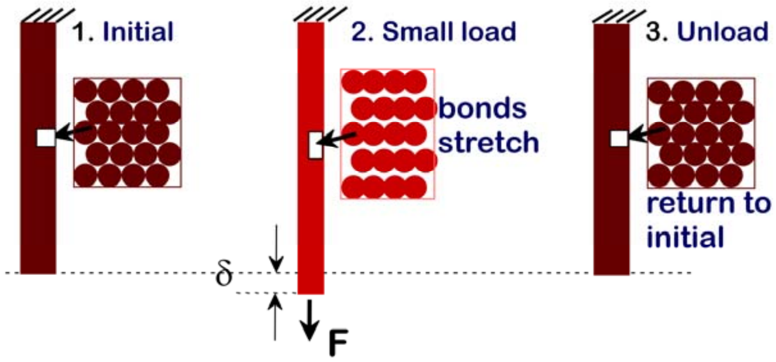
Stone pillared hall in the Vittala temple complex (15th Century CE), Hampi, Karnataka

Response of Materials to Stress

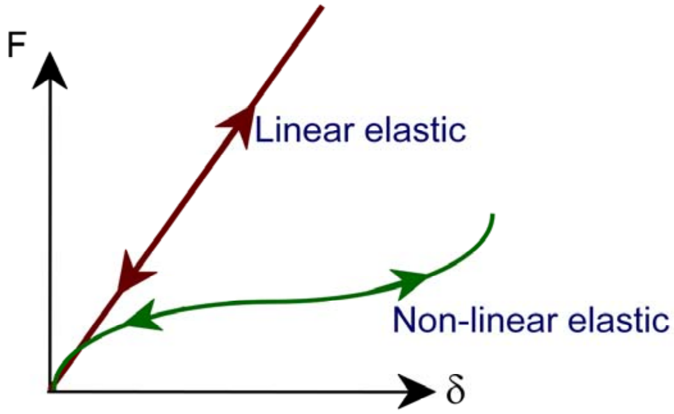
Modern Construction Materials – Lecture 7
Prof. Ravindra Gettu
IIT Madras

Deformation

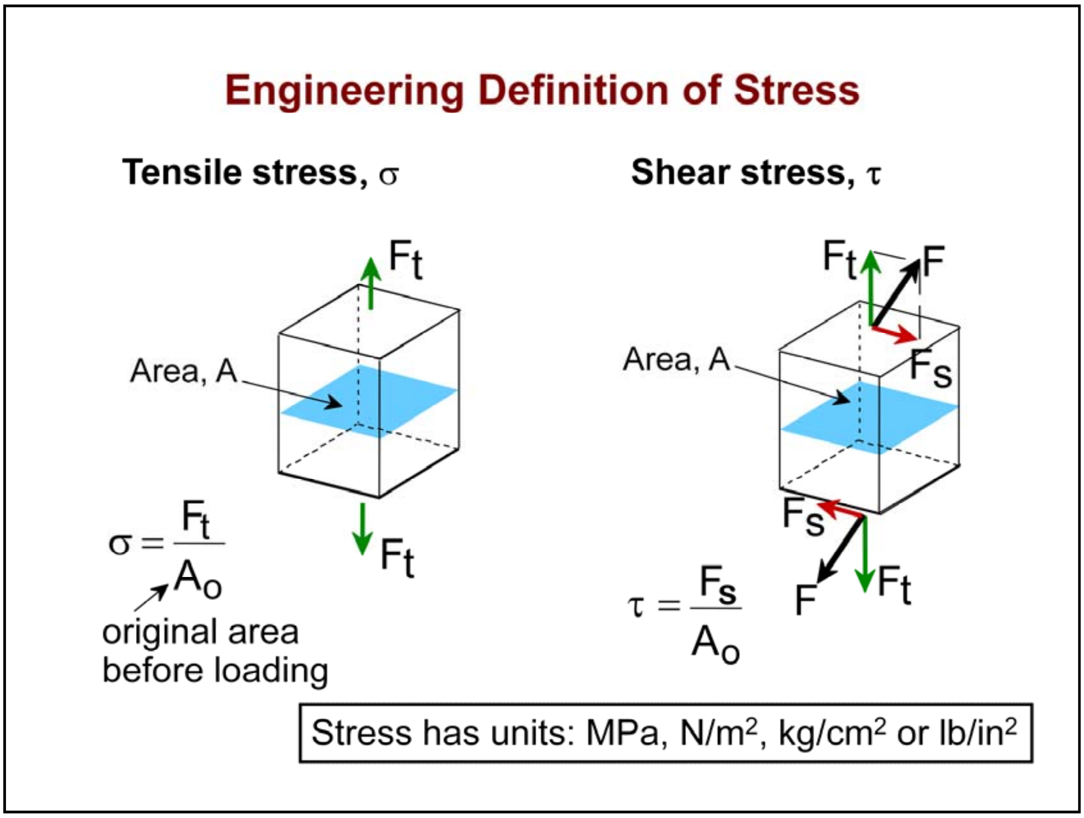
When a solid is subjected to external loading, it deforms instantaneously. In general, when the deformation is small, it is reversible.

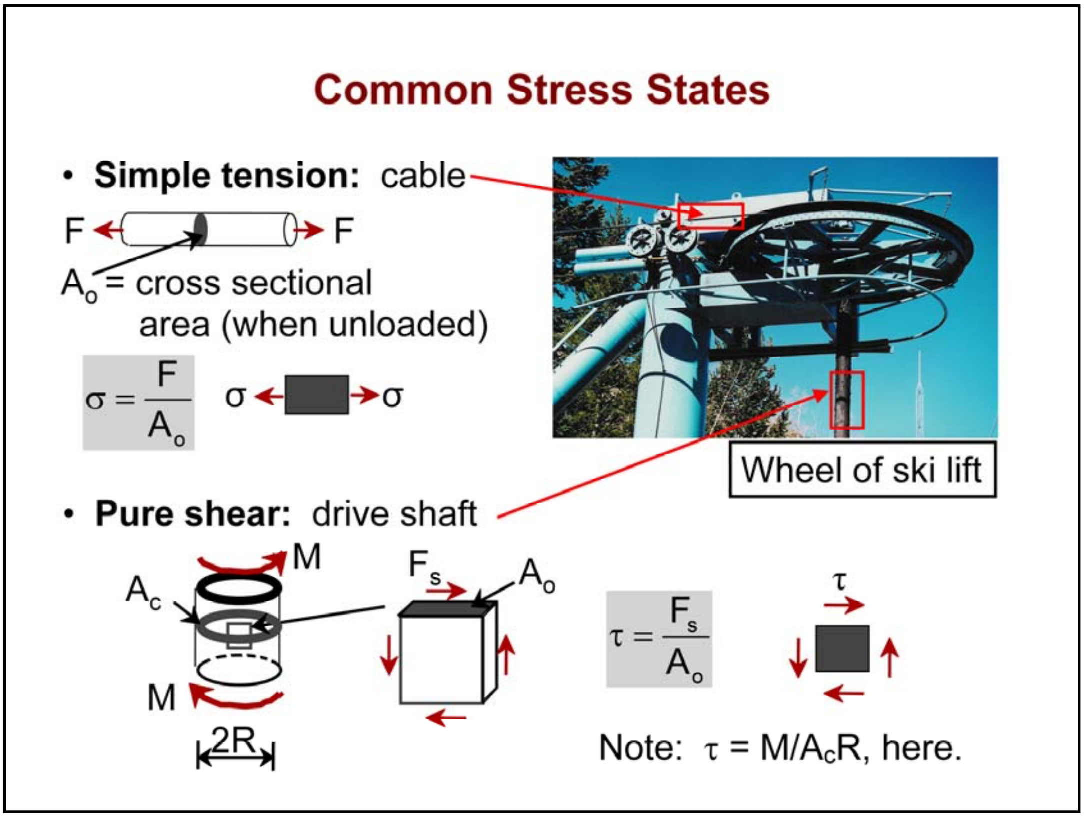


Deformation



Elastic means reversible or non-permanent


Engineering Definition of Stress
Tensile stress, σ
Shear stress, τ
Ft
Area, A
$\sigma = \frac{F_t}{A_o}$
original area
before loading
Ft
F
Fs
$\tau = \frac{F_s}{A_o}$
Stress has units: MPa, N/m2, kg/cm2 or lb/in2


Common Stress States
• Simple tension: cable
F
F
A_o = cross sectional
area (when unloaded)
σ = F / A_o
σ
σ
Wheel of ski lift
• Pure shear: drive shaft
M
A_c
M
2R
F_s
A_o
τ = F_s / A_o
τ
Note: τ = M/A_cR, here.

Common Stress States

- **Simple compression**

Stone Pillar, Hoysala Temple, Karnataka

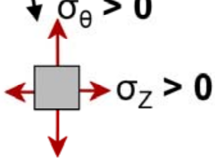
Bridge across Teesta River, Sikkim

$$\sigma = \frac{F}{A_o}$$

Common Stress States

- **Bi-axial tension**

Pressurized gas tank



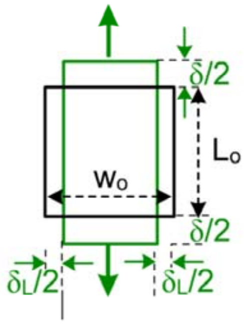
- **Hydrostatic compression**

Fish under water

Engineering Definition of Strain

- **Tensile strain**

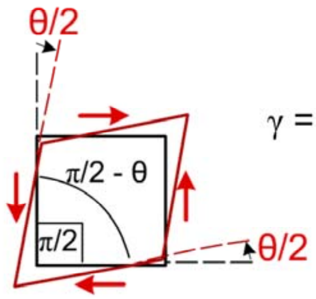
$$\varepsilon = \frac{\delta}{L_o}$$



- **Lateral strain**

$$\varepsilon_L = \frac{-\delta_L}{w_o}$$

- **Shear strain**



$$\gamma = \tan\theta$$

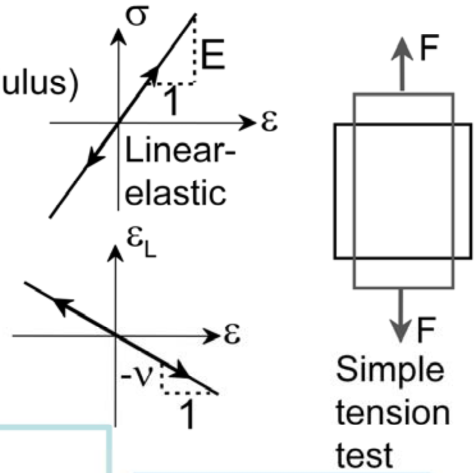
Strain is always dimensionless.

Elastic Properties

- Modulus of Elasticity, E:
  (also known as Young's modulus)

- Hooke's Law:
  $\sigma = E\,\varepsilon$

- Poisson's ratio, ν:
  $$\nu = -\frac{\varepsilon_L}{\varepsilon}$$



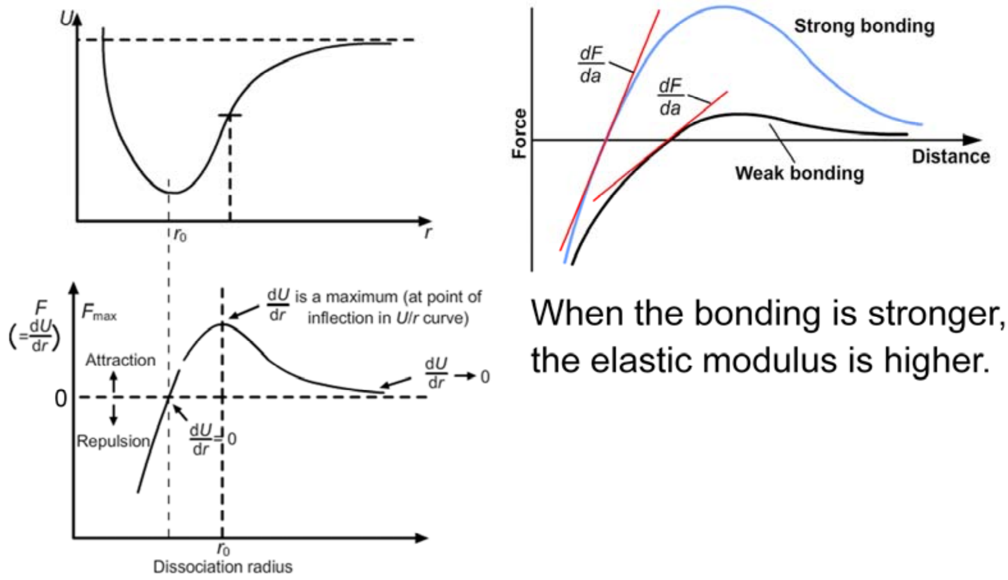
metals: $\nu \sim 0.33$

ceramics: $\nu \sim 0.25$; wood: $\nu \sim 0.16$

polymers: $\nu \sim 0.40$; rubber: $\nu \sim 0.50$

Units:
E: [GPa] or [psi]
ν: dimensionless

Elastic Modulus from Atomic Bonding



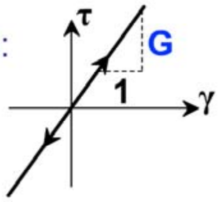
When the bonding is stronger, the elastic modulus is higher.

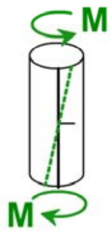
Ashby & Jones, Callister

Other Elastic Properties

Elastic Shear modulus, G:

$$\tau = G\,\gamma$$

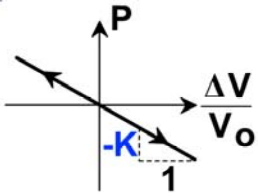


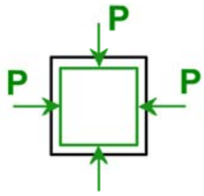


simple torsion test

Elastic Bulk modulus, K:

$$P = -K\frac{\Delta V}{V_o}$$





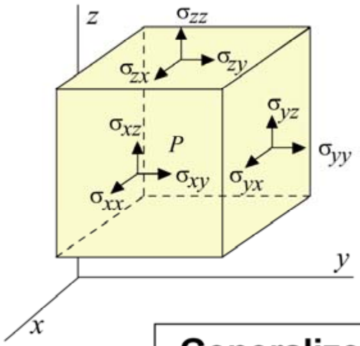
Special relations for isotropic materials:

$$G = \frac{E}{2(1+\nu)} \qquad K = \frac{E}{3(1-2\nu)}$$

pressure test:
Initial vol. = V_0
Vol. chg. = ΔV

General Three-Dimensional Relations

Components of Stress



Stress matrix

$$\begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}$$

Strain matrix

$$\begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix}$$

Generalized 3-D Hooke's Law

General Three-Dimensional Relations

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{zx} \\ \sigma_{xy} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{yz} \\ \varepsilon_{zx} \\ \varepsilon_{xy} \end{bmatrix}$$

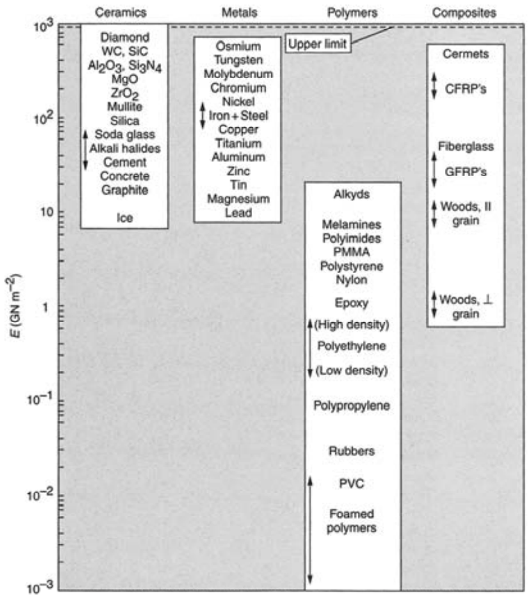
Stiffness matrix

Hooke's Law for Isotropic Elastic Material

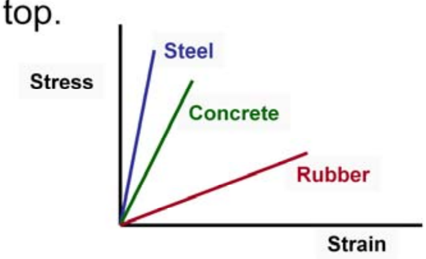
$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{zx} \\ \sigma_{xy} \end{bmatrix} = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & \nu & 0 & 0 & 0 \\ \nu & 1-\nu & \nu & 0 & 0 & 0 \\ \nu & \nu & 1-\nu & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-2\nu & 0 & 0 \\ 0 & 0 & 0 & 0 & 1-2\nu & 0 \\ 0 & 0 & 0 & 0 & 0 & 1-2\nu \end{bmatrix} \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{yz} \\ \varepsilon_{zx} \\ \varepsilon_{xy} \end{bmatrix}$$

This *constitutive relation* depends only on two material properties, E and ν.

Data for Young's Modulus

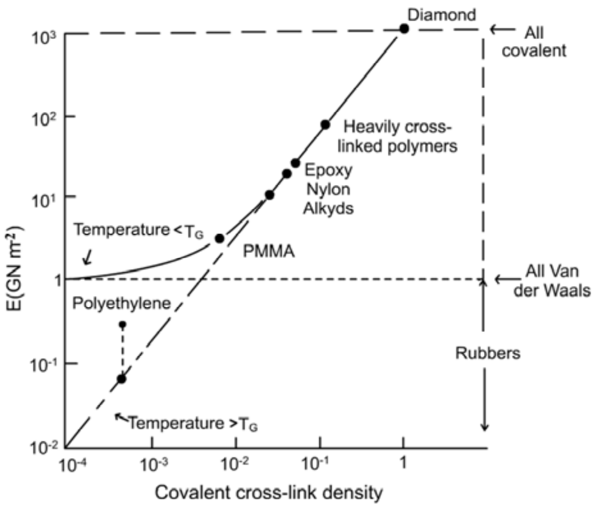


Most ceramics and metals have moduli in the range of 30-300 GPa;
Concrete (30 GPa) is near the bottom, aluminium (69 GPa) is higher up and steels (200 GPa) are at the top.



Ashby & Jones

Young’s Moduli of Polymers



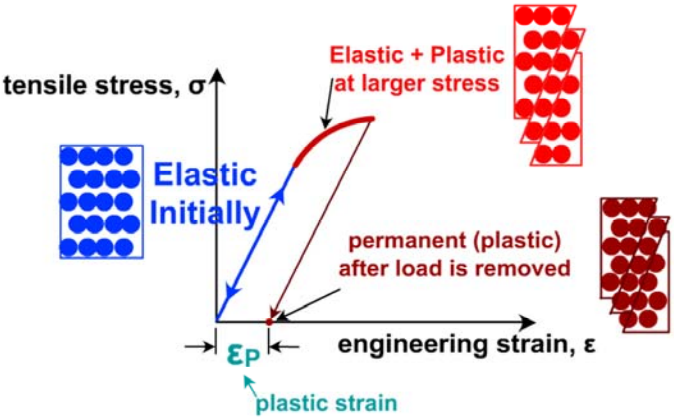
Young’s modulus increases with increasing density of covalent cross-links in polymers.

At higher temperatures, the Van der Waals bonds may melt and decrease the stiffness of the polymer.

Ashby & Jones

Plasticity (Permanent Deformation)

Under simple tension:



The yield strength is the stress where the stress-strain curve deviates from linearity.

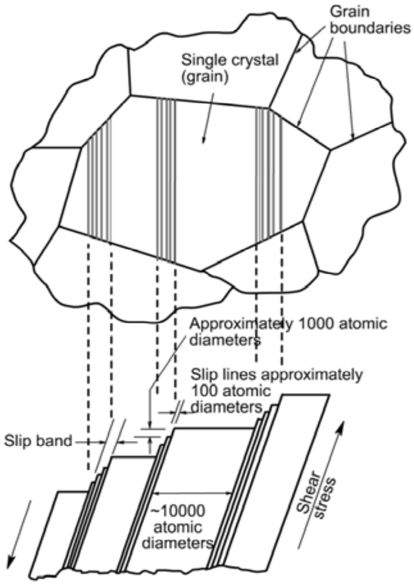
Yielding

- Elastic behaviour in metals and other materials can be terminated by the *yielding* of the material.
- Yielding involves the *permanent deformation* of the material, called as *plastic deformation*.
- Yielding enables the material to support larger strains before failure. This is often referred to as *ductility* or *ductile behaviour*.
- Yielding is generated by shear stresses.
- The most common mechanism of yielding in crystalline materials is *slip* (through dislocation movement in metals).

Young et al.

Slip Along Atomic Planes

Slip in a single crystal commences on the most favourably oriented slip system when the shear stress along the corresponding plane reaches some critical value.



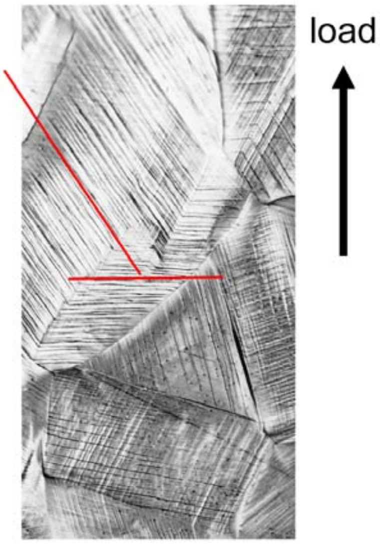
Slip in Polycrystalline Solids

Slip planes and directions change from one crystal to another.

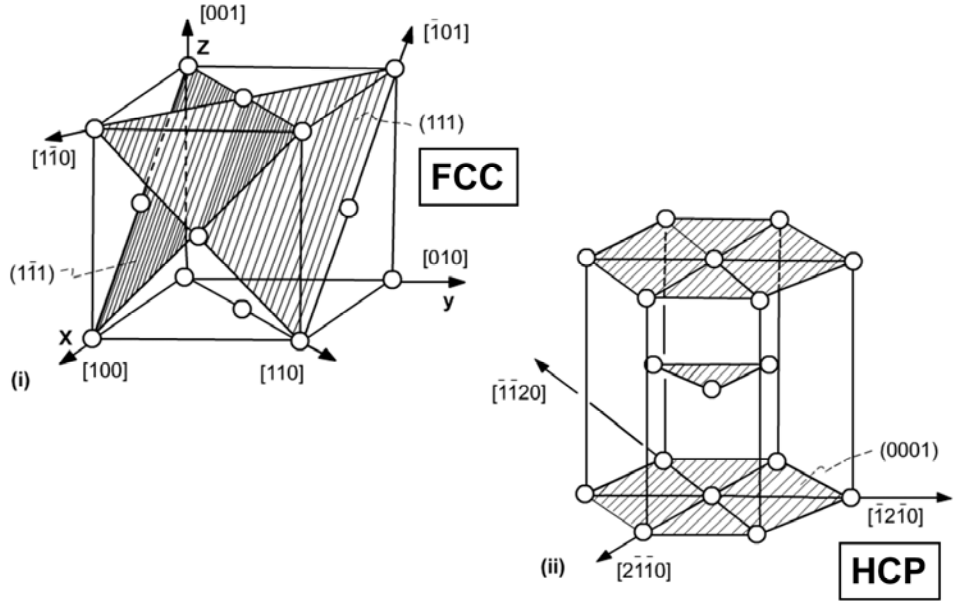
Materials with crystal structures having more slip systems undergo plastic deformation more easily.

For example, Aluminium and Copper, with the FCC structure (12 planes) are more malleable and ductile than zinc, which has a HCP structure (3 parallel planes).

Slip lines on surface of polycrystalline Cu



Slip in Polycrystalline Solids



Yielding in Polycrystalline Materials

- In polycrystalline materials, slip will first begin in grains that are most favourably oriented with respect to the maximum shear stress, and then will progress successively to the less favourably oriented crystals. In addition, there will be movement along the grain boundaries.

- Since yielding does not occur throughout the material at the same time, the yield point is not sharply defined.

Yielding in Polycrystalline Materials

- The yield strength is considerably higher than that of a single crystal of the same material since many slip systems must become active before generalised yielding can occur.
- The grain boundaries act as barriers to dislocation movement, which further delays the onset of yield.

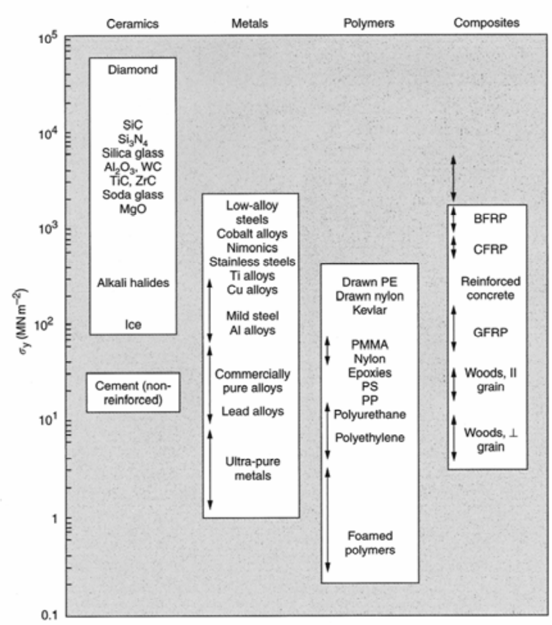
Young et al.

Yielding in Amorphous Materials

- In amorphous materials, several different mechanisms are responsible for yielding.
- In thermoplastic polymers, yielding is due to the slip of the long chain molecules past each other. However, this process is highly time-dependent, so the response of these materials depends on the rate of loading.

Young et al.

Data for Yield Strength



Most ceramics have very high yield strengths. However, almost all of them fracture before yielding.

Pure metals have low yield strengths (i.e., they are soft), which is the reason they have been used historically for jewellery and weapons.

Polymers, in general, have lower yield strengths than metals.

Ashby and Jones

Case Study: Plastic (No-Yield) Design

Choice of material for a pressure vessel

- Material selection based on the ability to contain gas at a pressure *p*, minimum weight and lowest possible cost, without plastic collapse (i.e., general yield).

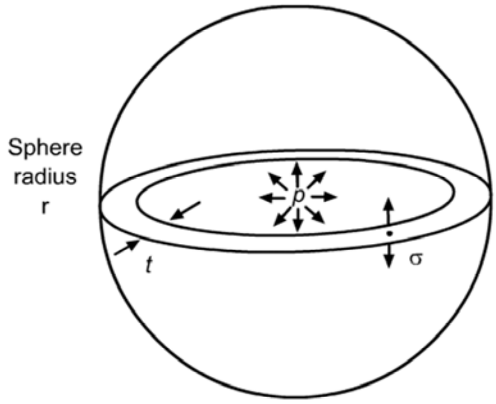
- The design problem is over-simplified, since
  - Such structures can also fail by fracture (i.e., rupture), fatigue and corrosion.
  - Constructability often governs material choice.

Case Study: Plastic (No-Yield) Design

Stress in the vessel wall is:
$\sigma = pr / 2t$

The radius of the pressure vessel, r, is fixed by the design.

For safety, $\sigma \leq \sigma_y / S$, where S is the safety factor.



The vessel mass is $M = 4\pi r^2 t \rho$, where ρ is the density of the material.

So, $$t = \frac{M}{4\pi r^2 \rho}$$

Ashby and Jones

Case Study: Material Selection in Plastic Design of Pressure Vessel

Candidate materials for pressure vessels and their properties

Material	σ_y (MPa)	ρ (kg/m^3)	Cost, C (Rs/kg)	ρ / σ_y	$C.\rho / \sigma_y$
Reinforced concrete	200	2500	5	13	65
Alloy steel (pressure vessel steel)	1000	7800	20	8	160
Mild steel	220	7800	10	36	360
Aluminium alloy	400	2700	40	7	280
Fiber glass	200	1800	100	9	900
CFRP	600	1500	2,000	3	6,000

σ_y = yield strength; ρ = unit weight; C = cost per kg

Ashby and Jones

Case Study: Material Selection in Plastic Design of Pressure Vessel

Material selection based on minimum weight:

(Relevant in the design of an aircraft body, spacecraft hull, rocket fuel tank)

$$\frac{\sigma_y}{S} \geq \frac{2\pi p r^3 \rho}{M} \quad \text{or, the minimum mass} \quad M = 2S\pi p r^3 \left(\frac{\rho}{\sigma_y}\right)$$

Therefore, for minimum weight, we require the smallest (ρ/σ_y)

From the previous table, the best choice of the lightest vessel is CFRP. Aluminium alloy and pressure-vessel steel are next.

Ashby and Jones

Case Study: Material Selection in Plastic Design of Pressure Vessel

Material selection based on minimum cost:

(Relevant in the design of a water tank, pressure vessel of nuclear reactor, natural gas tank)

$$CM = 2CS\pi p r^3 \left(\frac{\rho}{\sigma_y} \right)$$ should be minimised.

where C is the cost per unit weight.

Therefore, we require the smallest value of $(C.\rho/\sigma_y)$

From the previous table, the best choice for the cheapest vessel is reinforced concrete. The next is pressure-vessel steel.

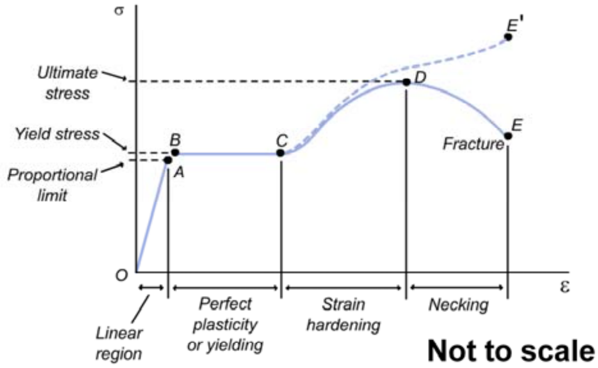
Ashby and Jones

Post-Yield Behaviour

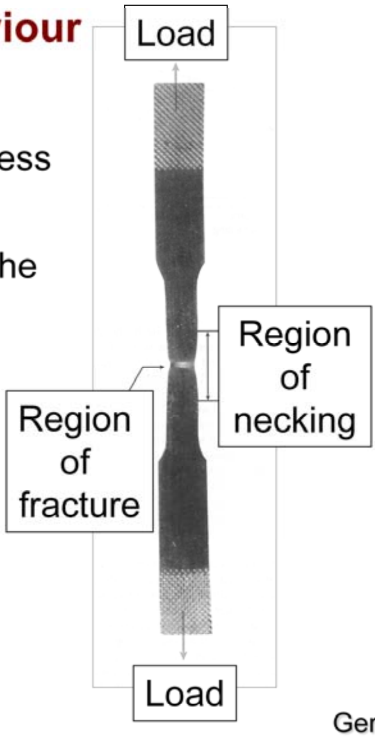
Stress-Strain Diagram (in Tension)

When the initial area is used in the stress calculation, it is called nominal stress.

When actual area of bar is used, it is the true stress.

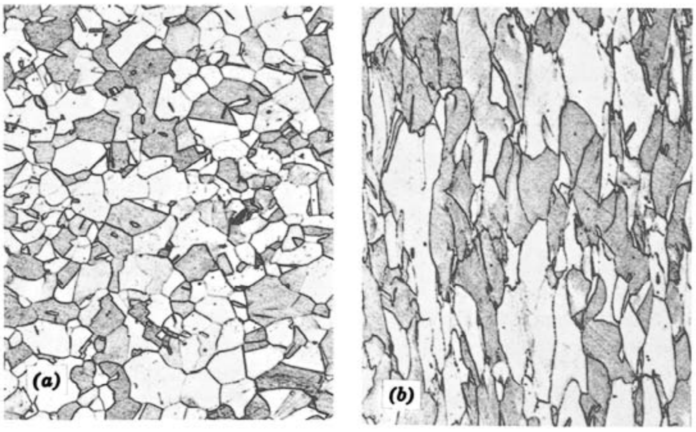


Not to scale



Gere

Post-Yield Behaviour



Alteration of the grain structure of a polycrystalline material due to plastic deformation. (a) Equiaxed grains before deformation, (b) Elongated grains after deformation (170 X)

Callister

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Lotus Mahal, masonry structure, Zenana Enclosure (15th Century CE), Hampi, Karnataka

Response of Materials to Stress

Modern Construction Materials – Lecture 7 continued

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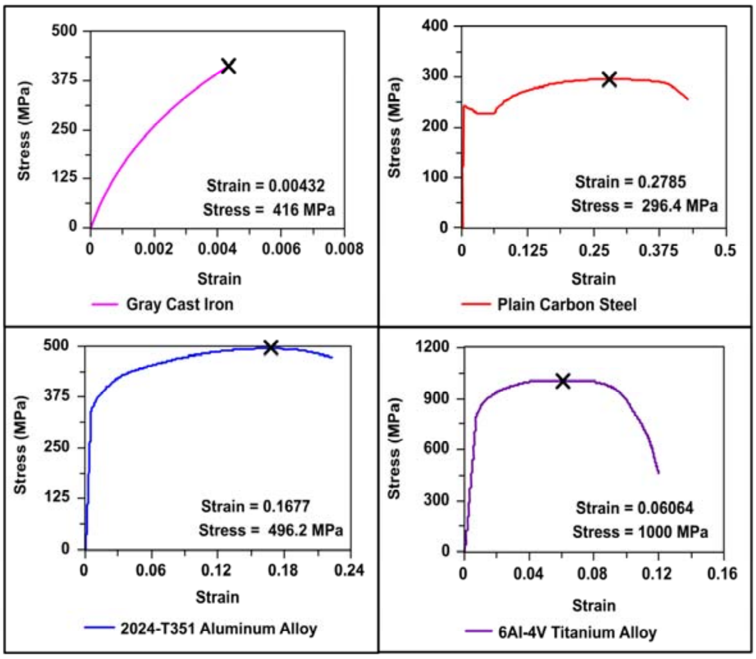
Stress-Strain Diagrams (in Tension)



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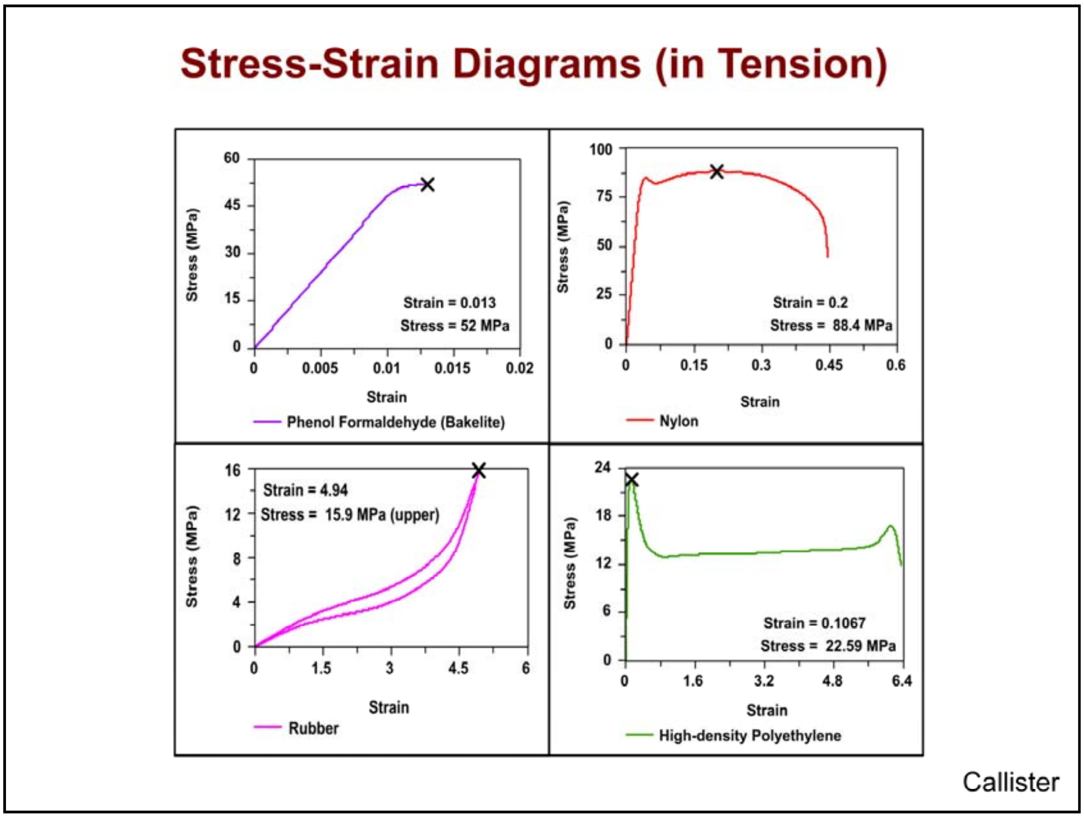
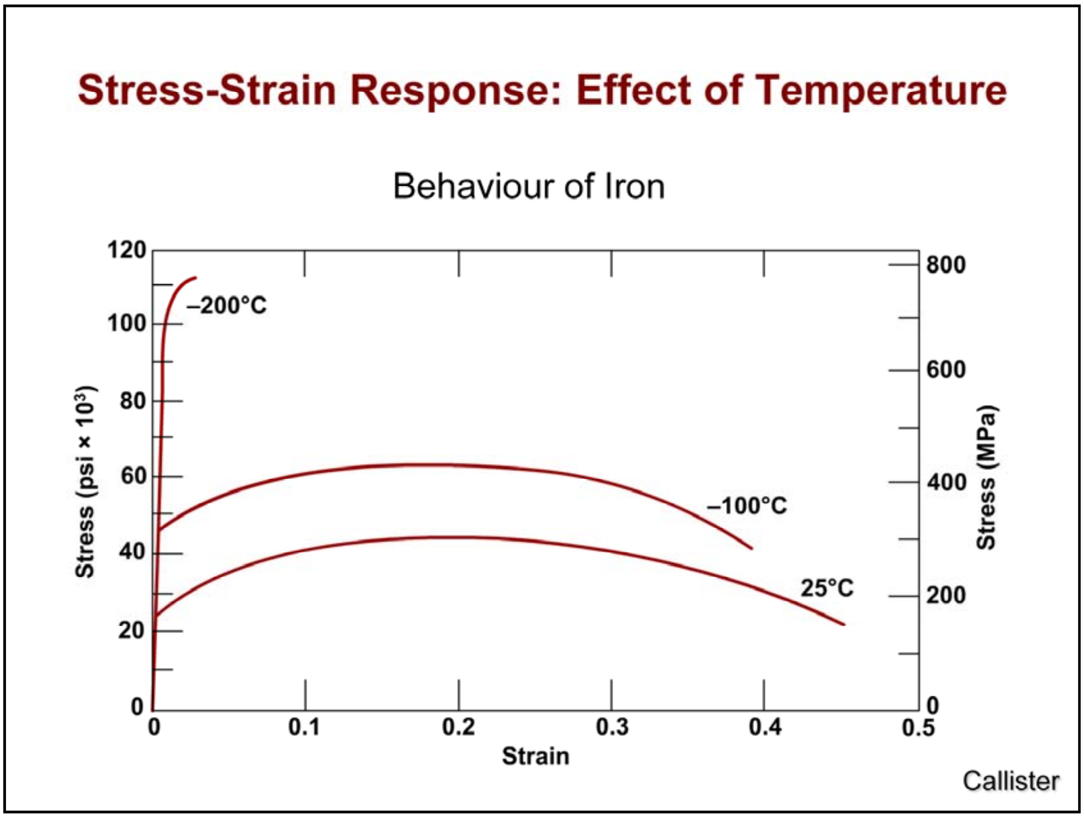
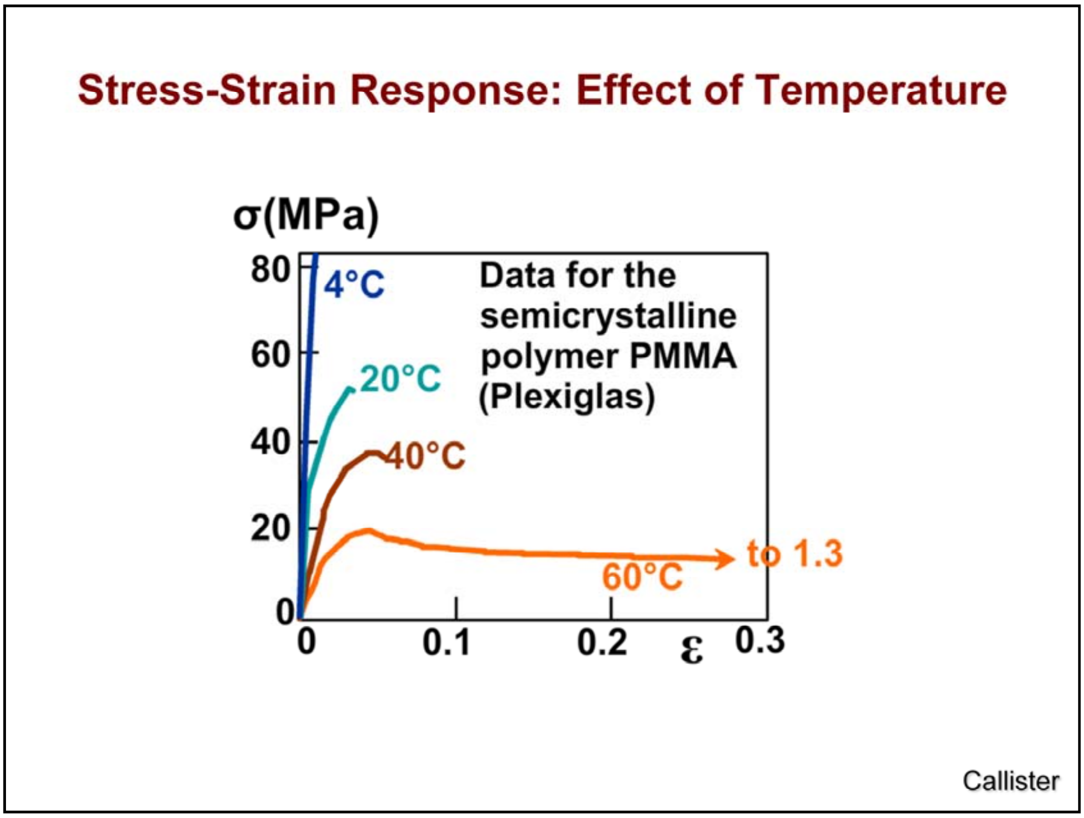

Stress-Strain Diagrams (in Tension)
Stress (MPa)
Strain
Strain = 0.013
Stress = 52 MPa
Phenol Formaldehyde (Bakelite)
Strain = 0.2
Stress = 88.4 MPa
Nylon
Strain = 4.94
Stress = 15.9 MPa (upper)
Rubber
Strain = 0.1067
Stress = 22.59 MPa
High-density Polyethylene
Callister


Stress-Strain Response: Effect of Temperature
Behaviour of Iron
120
100
80
60
40
20
0
Stress (psi × 10³)
800
600
400
200
0
Stress (MPa)
–200°C
–100°C
25°C
0
0.1
0.2
0.3
0.4
0.5
Strain
Callister

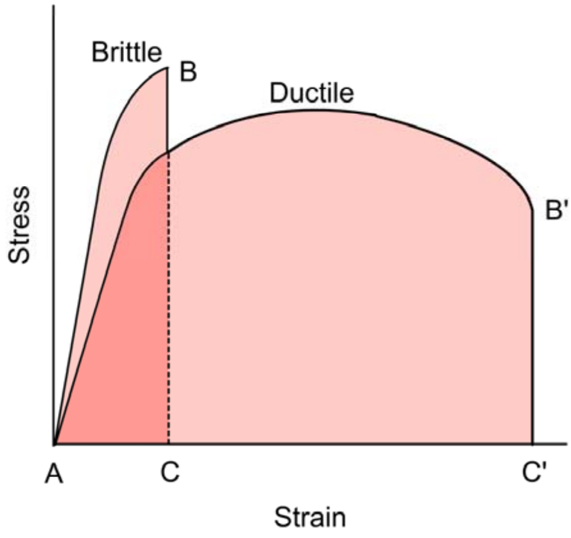

Stress-Strain Response: Effect of Temperature
σ(MPa)
80
60
40
20
0
4°C
20°C
40°C
60°C
to 1.3
Data for the
semicrystalline
polymer PMMA
(Plexiglas)
0
0.1
0.2
ε
0.3
Callister

Stress-Strain Response

- The modulus of elasticity, and yield and tensile strengths decrease with an increase in temperature.
- However, ductility generally increases with an increase in temperature.

Stress-Strain Response

Ductility and Brittleness



Stress-Strain Response

Ductility is a measure of the deformation at fracture.

Defined by

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

(where l_0 and l_f are the initial and final lengths)

or

Percent reduction in area $\longrightarrow$ $\%RA = \left(\frac{A_0 - A_f}{A_0}\right) \times 100$

(where A_0 and A_f are the initial and final areas)

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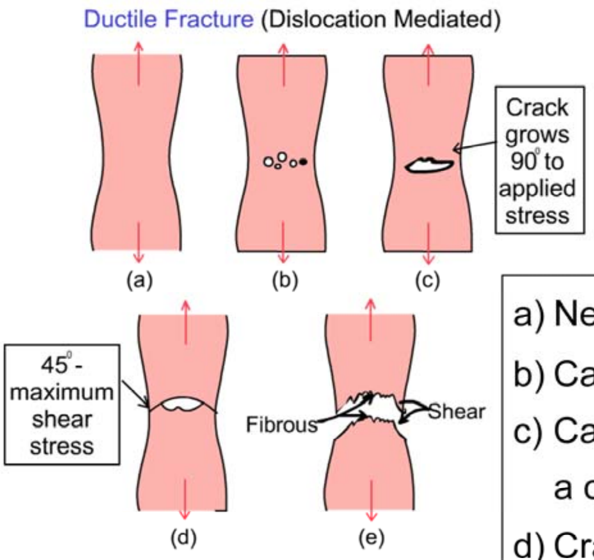
Ductile Failure



a) Necking,

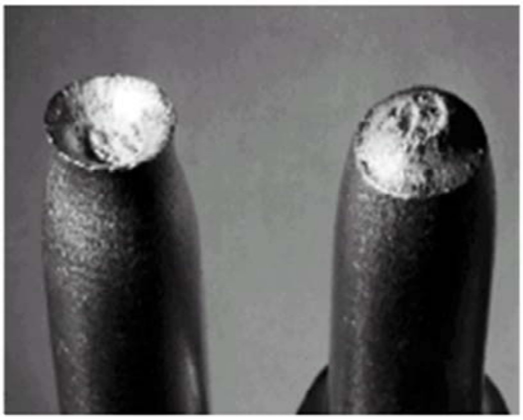
b) Cavity formation,

c) Cavity coalescence to form a crack,

d) Crack propagation,

e) Fracture

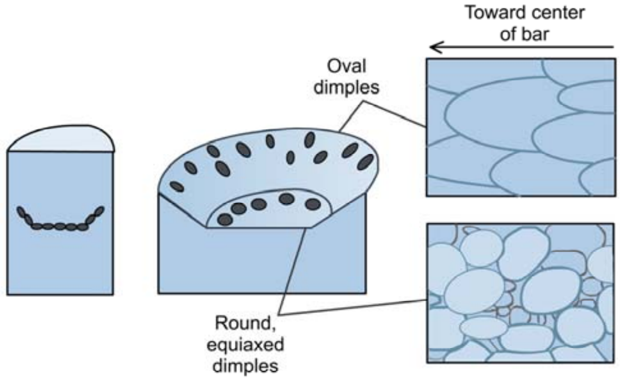
Ductile Failure (Dislocation Controlled)



Cup-and-Cone failure in Aluminium

Ductile Failure

Dimples form during ductile fracture. Equiaxed dimples form in the center, where microvoids grow. Elongated dimples, pointing toward the origin of failure, form on the shear lip

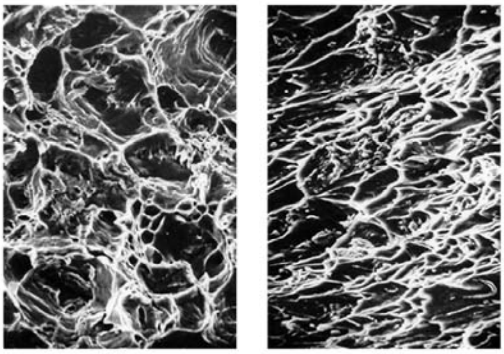


Ductile Failure

Scanning electron micrographs of an annealed 1018 steel exhibiting ductile fracture in a tensile test.

(a) Equiaxed dimples at the flat center of the cup and cone, and

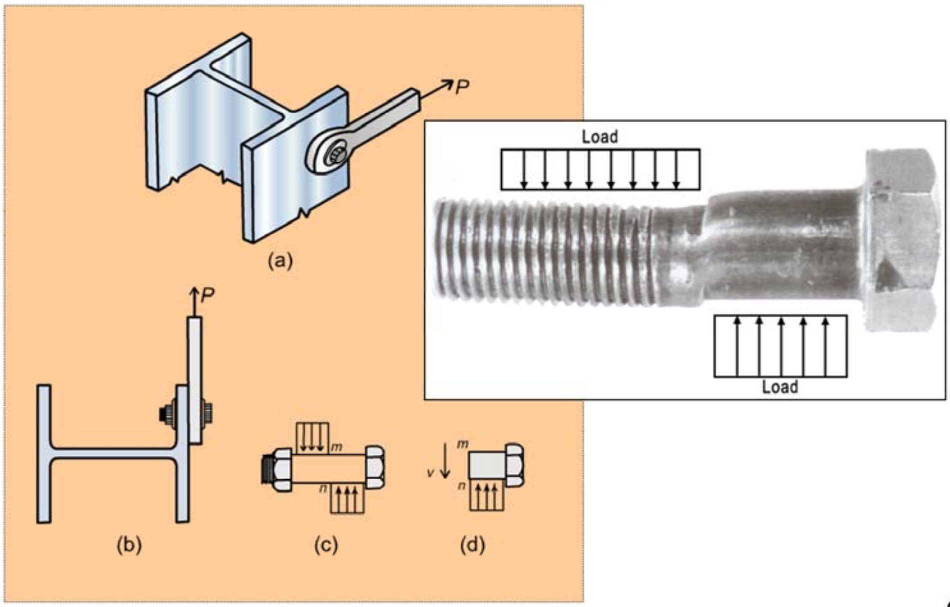
(b) elongated dimples at the shear lip (x 1250)



(a) (b)

Ductile Failure

Shear - Metal bolt under pure shear



Gere

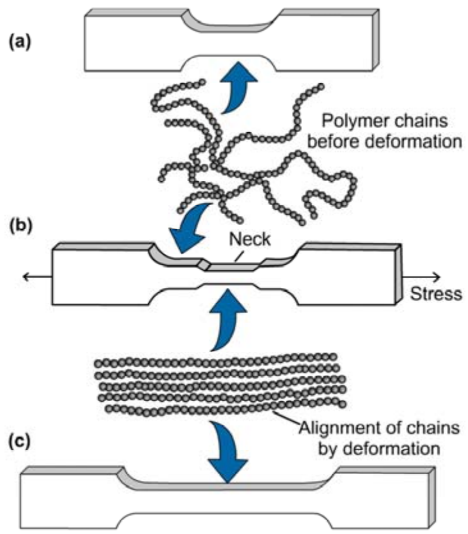
Ductile Failure

Compression - Wood under axial compression

Slip due to shear deformation of the wood fibres

Gere

Strain Hardening of Polymers



In an undeformed thermoplastic polymer tensile bar,

(a) the polymer chains are randomly oriented.

(b) When a stress is applied, a neck develops as chains become aligned locally. The neck continues to grow until the chains in the entire gage length have aligned.

(c) The strength of the polymer is increased

Strain Hardening of Metals

- *Strain hardening* is the phenomenon that makes a ductile metal harder and stronger as it is plastically deformed. It is also called *work hardening* or *cold working*.
- The degree of plastic deformation is expressed as *percent cold work*:

$$\%CW = \left(\frac{A_0 - A_d}{A_0}\right) \times 100$$

  where A_0 is the original area of the stressed cross section and A_d is the area after deformation.
- Yield and tensile strengths increase with increasing cold work but ductility decreases.

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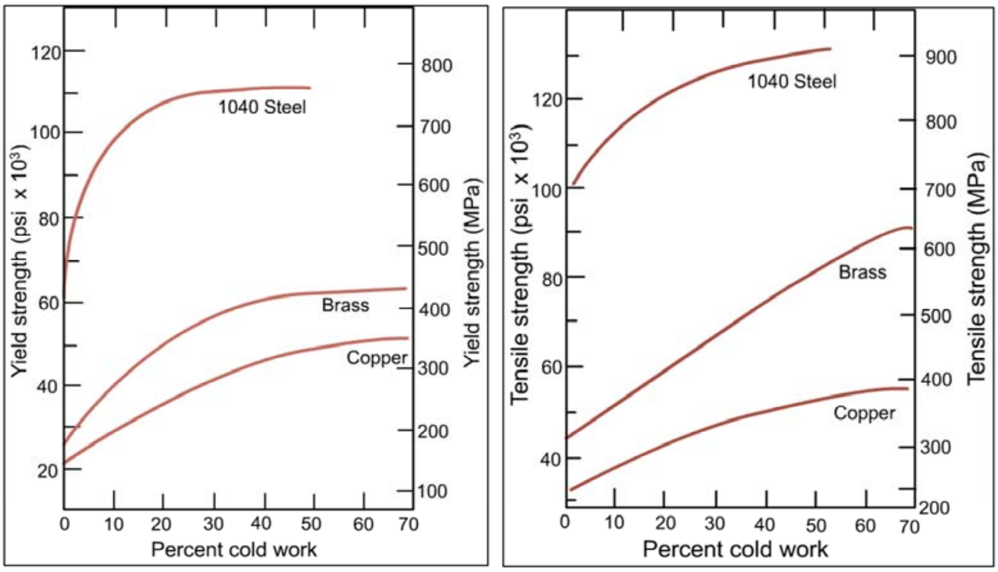
Strain Hardening of Metals



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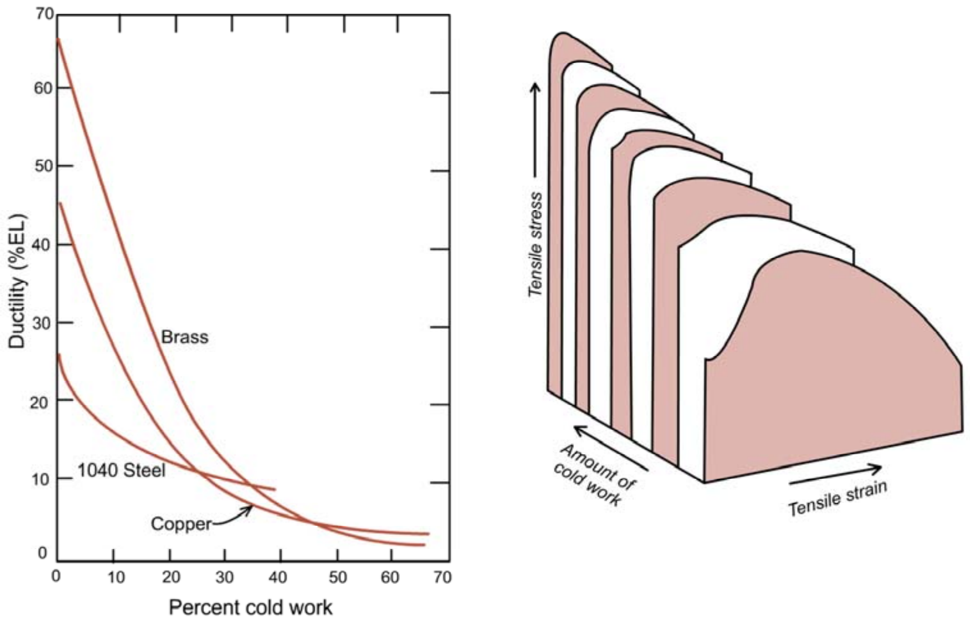
Strain Hardening of Metals



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Strain Hardening of Metals

- *Strain hardening* is explained on the basis of dislocation-dislocation strain field interactions.
- The dislocation density in a metal increases with deformation or cold work. Consequently, the separation between dislocations decreases.
- Since the motion of dislocations is hindered by the presence of other dislocations, the resistance to dislocation motion increases with an increase in the dislocation density. As a result, the stress necessary to deform a metal increases with increasing cold work.
- The effect of strain hardening may be removed by an *annealing* heat treatment.

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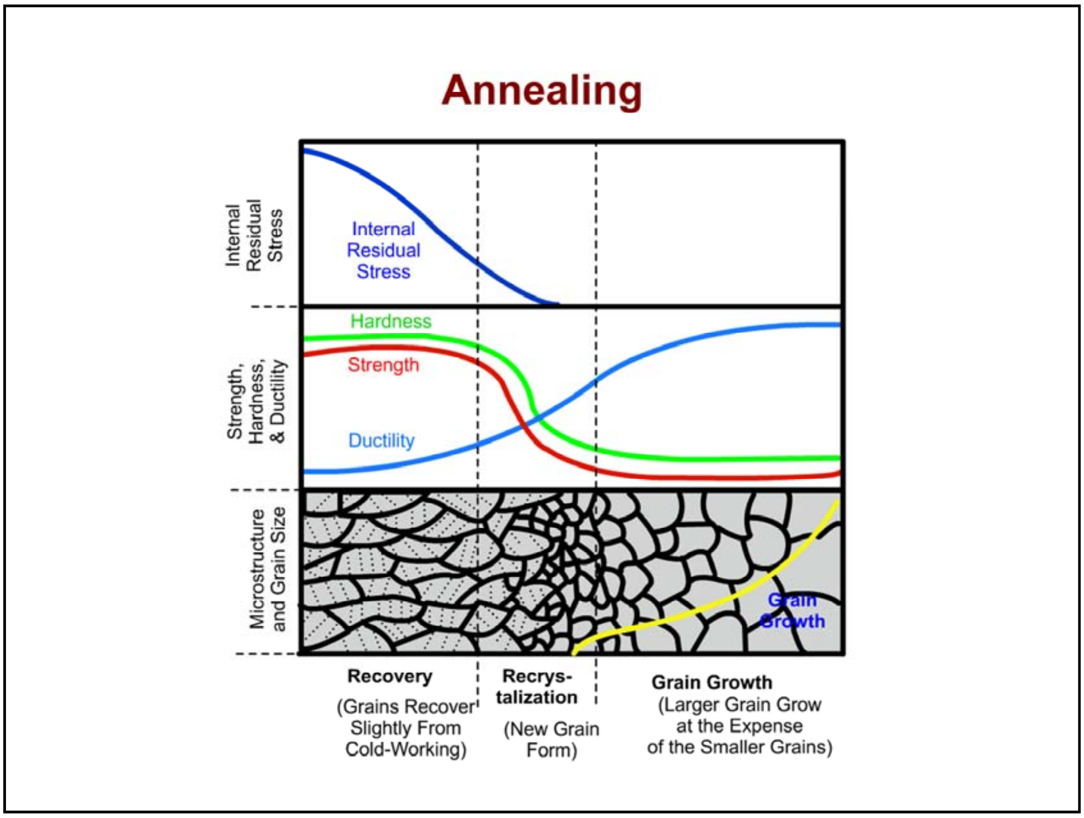
Annealing

- The properties and structure of cold worked metal can revert back to the pre-cold worked states by appropriate heat treatment.
- Such heat treatment, called annealing, consists of three stages: recovery, recrystallisation and grain growth.


Annealing
Internal Residual Stress
Internal Residual Stress
Strength, Hardness, & Ductility
Hardness
Strength
Ductility
Microstructure and Grain Size
Grain Growth
Recovery
(Grains Recover Slightly From Cold-Working)
Recrys-talization
(New Grain Form)
Grain Growth
(Larger Grain Grow at the Expense of the Smaller Grains)

Annealing

– **Recovery** - A low-temperature heat treatment designed to eliminate residual stresses introduced during deformation without reducing the strength of the cold-worked material.

– **Recrystallization** - A medium-temperature heat treatment designed to eliminate all of the effects of the strain hardening produced during cold working.

– **Grain growth** - Movement of grain boundaries by diffusion in order to reduce the amount of grain boundary area.

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Annealing

The following photomicrographs (75×) show several stages of recrystallisation and grain growth in brass.

a) Cold worked (33% CW) grain structure

b) Initial stages of recrystallisation after heating 3 s at 580°C

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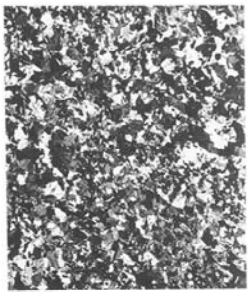
Annealing

c) Partial replacement of cold-worked grains by recrystallised ones (4 s at 580°C)

d) Complete recrystallisation (8 s at 580°C)



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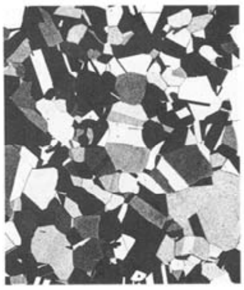
Annealing



e) Grain growth after 15 min at 580°C

f) Grain growth after 10 min at 700°C

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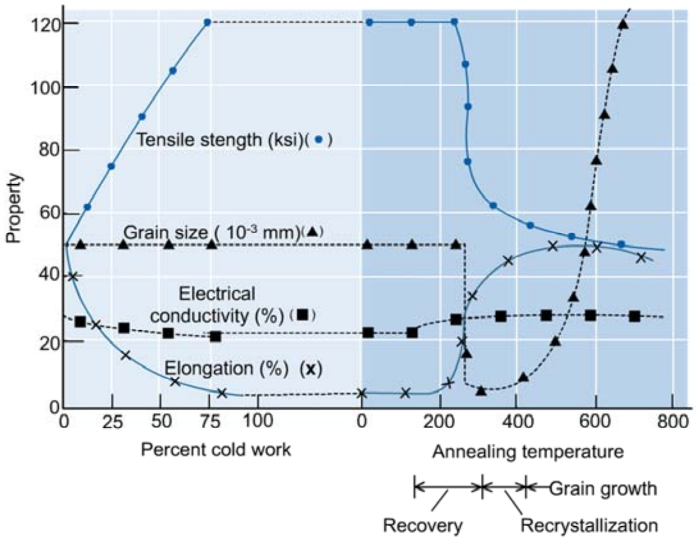
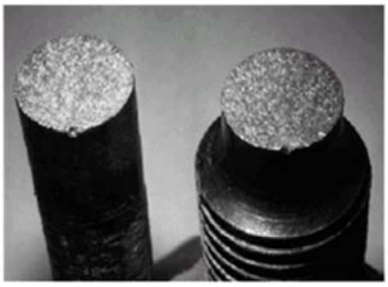
Cold-working and Annealing



The effect of cold work on the properties of a Cu-35% Zn alloy, and the effect of annealing temperature on the same alloy that is cold-worked 75%.

Brittle Fracture

- *Brittle fracture* takes place without any appreciable deformation, and by rapid crack propagation.
- The direction of cracking is generally perpendicular to the direction of applied tensile stress, and yields a relatively flat fracture surface.



Brittle fracture in mild steel

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Ductile-to-Brittle Transition

- In many materials the failure mode changes from ductile-to-brittle as the temperature decreases. Normally, this transition occurs over a range of temperatures.
- Not all metal alloys exhibit a ductile-to-brittle transition. Those having an FCC crystal structure (e.g., Al and Cu alloys) remain ductile even at very low temperatures while BCC and HCP alloys experience this transition.
- Most ceramics and polymers also experience a ductile-to-brittle transition.

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Ductile-to-Brittle Transition: *Failure of Ships*

SINKING OF THE TITANIC

"Cold water temperatures, about 35°F, caused the steel to crack in a brittle manner, like glass, when it hit the iceberg, instead of the ductile, twisting, tearing manner, we are all accustomed. During the first half 20th century, the temperature above which typical high grade ship steel changed to ductile, tearing failure mode from the brittle mode was 50°F. Not until 1963, over 50 years after the TITANIC sank in cold arctic water, was the first authoritative documentation published by two researchers from the U. S. Naval Research Laboratory providing a comprehensive, quantitative analysis describing the phenomenon of ductile to brittle crack propagation in steel."

http://www.disastercity.com/titanic/index.shtml

Ductile-to-Brittle Transition: *Failure of Ships*

FAILURE OF LIBERTY SHIPS

The engineering community was so clueless as to the low temperature brittle fracture of steel problem that over 5000 Liberty ships were mass produced during World War II without accounting for this phenomenon. Of these 5000 Warships, 1000 suffered significant failures between 1942-1946 because of low temperatures, while 200 suffered serious fractures between 1942-1952. No one may ever know exactly how many ships "just disappeared" in the North Atlantic and were falsely chalked up as lost to German U-Boat torpedo attacks due to low temperature brittle fractures.

Quoted from http://www.disastercity.com/titanic/index.shtml

Ductile-to-Brittle Transition: *Failure of Ships*

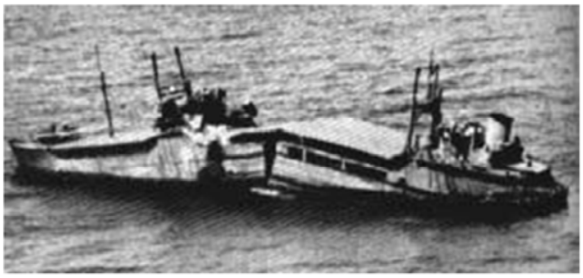
The Government knew something was wrong, because the failure rate of the welded Liberty ships was statistically astronomical in the North Atlantic, while literally non-existent in the warm waters of the South Pacific.

Not until 1947, that a ship literally broke into two pieces while tied to a dock in the cold water of Boston Harbor, that there was enough evidence, left accessible and dramatic enough, that the problem was taken seriously.

Quoted from http://www.disastercity.com/titanic/index.shtml

Ductile-to-Brittle Transition: *Failure of Ships*

FAILURE OF LIBERTY SHIPS



Brittle Fracture

- In an ideal material, fracture can be visualised as the pulling apart and breaking of interatomic bonds across two neighbouring planes. However, real materials fracture at tensile stresses that are much lower (about two orders of magnitude lower) than the theoretical stress needed to break the interatomic bonds.

- This difference in the real and theoretical tensile strength is attributed to the presence of defects (i.e., tiny cracks) that propagate under stress, leading to a lower tensile strength (Griffith, 1920).

Brittle Fracture

- It has been shown that surface cracks are more effective in causing fracture than internal cracks.

- The resistance of a material to crack propagation is called *fracture toughness*.

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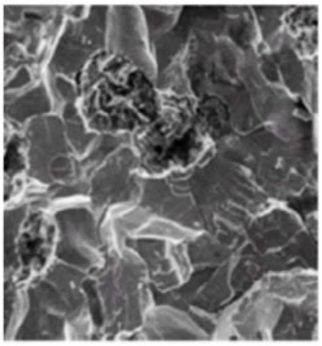
Brittle Fracture

- *Transgranular (or cleavage) fracture* (A): Crack passes through grains, along crystallographic planes.
- *Intergranular fracture* (B): Cracking is along the grain boundaries.



A

B

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Methods of Protection Against Brittle Fracture

- *Surface treatment* is the most important method used to protect against fracture in brittle materials.
- Etching of glass (with hydrofluoric acid) removes the surface layer and the cracks in it. Consequently, etched glass has a higher strength than unetched glass, until abrasion and other actions scratch the surface. Freshly drawn glass fibres are covered with a resin to protect their surfaces.
- Compressive stresses can be induced on the surface to prevent tensile opening of the cracks. Tempering and ion exchange are processes which produce a precompressed surface in glass.

Raghavan

Department of Civil Engineering
IIT Madras

Photographs of the ruins of the 15th-century city of Vijayanagara, near Hampi, Karnataka

Response of Materials to Stress

Modern Construction Materials – Lecture 7 continued

Prof. Ravindra Gettu
IIT Madras

Fatigue Failure

- Fatigue is a type of failure that occurs in structures subjected to dynamic fluctuating stresses (e.g., bridges, aircraft and machine components).
- Under these circumstances it is possible for failure to occur at a stress level lower than the tensile or yield strength for a static load.
- Fatigue failure is brittle in nature even in ductile metals, with little plastic deformation associated with failure.

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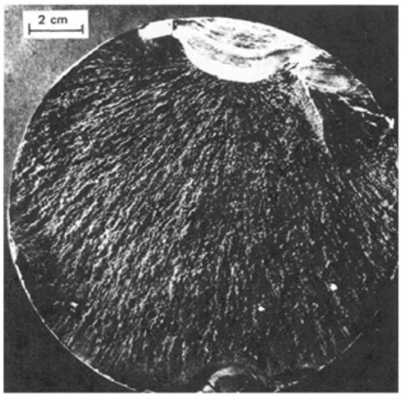
Fatigue Failure

The process of fatigue failure has three stages:

1. crack initiation where a tiny crack forms at some point of high stress concentration,
2. crack propagation, where the crack advances incrementally during each loading cycle,
3. final failure, which occurs rapidly once the crack has reached a critical size.

Fatigue Failure



Fatigue failure surface. A crack formed at the top edge. The smooth region near the top is the area over which the crack propagated slowly. Rapid failure occurred over the area having a dull and fibrous texture (0.5X)

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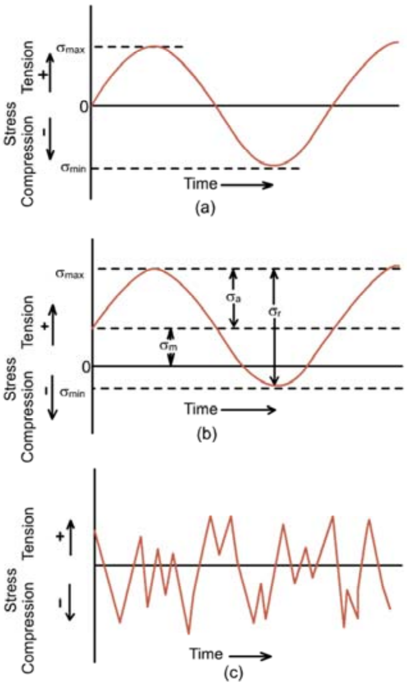
Fatigue Failure: Cyclic stresses



Variations of stress with time that can account for fatigue failure.

(a) Reversed stress cycle, symmetric tensile-compressive cycles

(b) Repeated stress cycle, asymmetric with respect to zero stress level

(c) Random stress cycle

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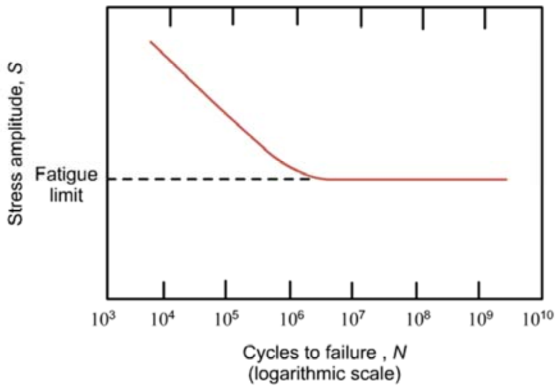
Fatigue Failure: *S-N* curves

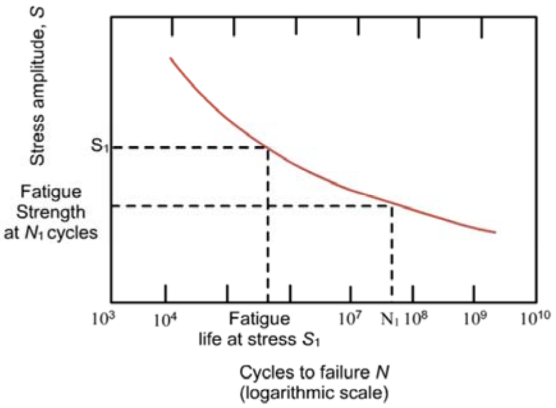
Variation of stress with logarithm of the number of cycles to failure.

(a) For some ferrous and titanium alloys, the *S-N* curve becomes horizontal at higher *N* values; i.e., there is a limiting stress level, called the *fatigue limit*, below which fatigue failure will not occur.



(a)

Fatigue Failure: *S-N* curves



(b)

(b) Most nonferrous alloys do not have a fatigue limit; i.e., the *S-N* curve continues its downward trend at increasingly greater values of *N.*

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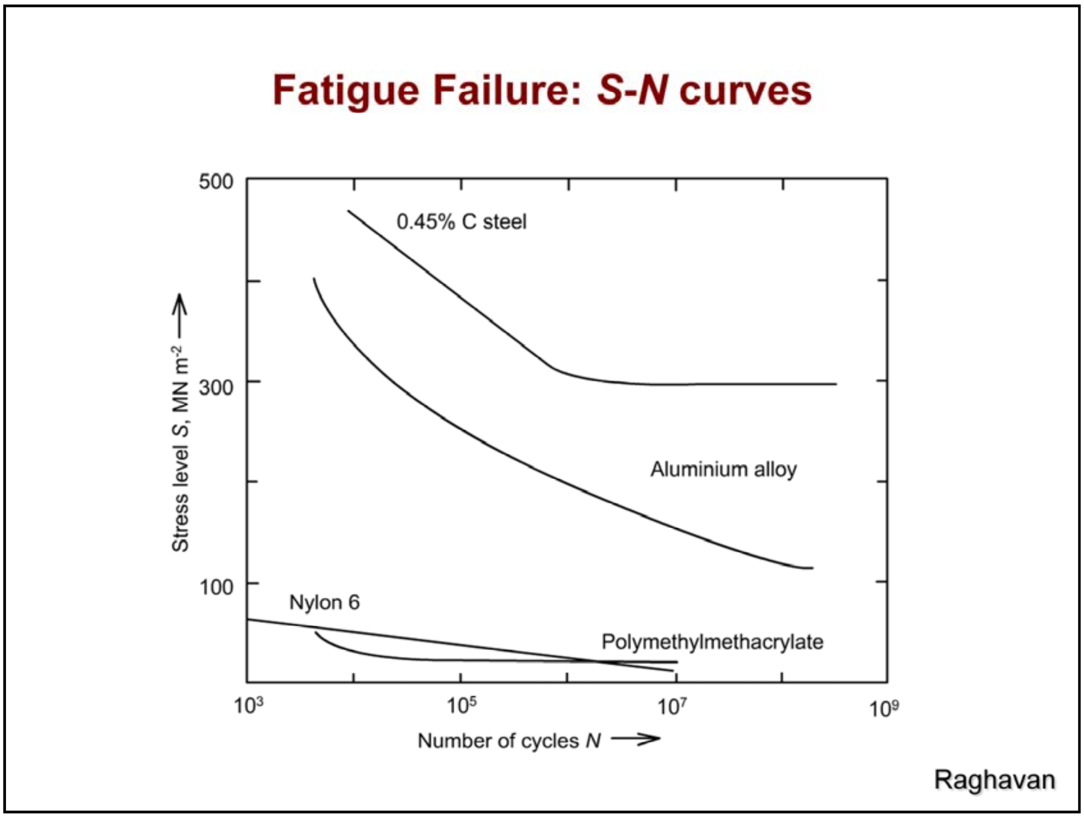
Fatigue Failure: S-N curves
500
300
100
Stress level S, MN m-2
0.45% C steel
Aluminium alloy
Nylon 6
Polymethylmethacrylate
10³
10⁵
10⁷
10⁹
Number of cycles N
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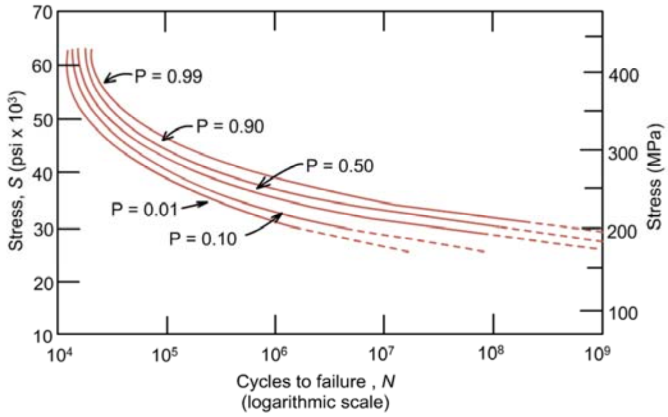
Fatigue Failure: *S-N* curves

Fatigue failure is probabilistic

Since there is significant scatter is fatigue test data, *S-N* curves are often plotted in terms of probabilities.

S-N curves for a 7075 -T6 aluminium alloy; P denotes the probability of failure



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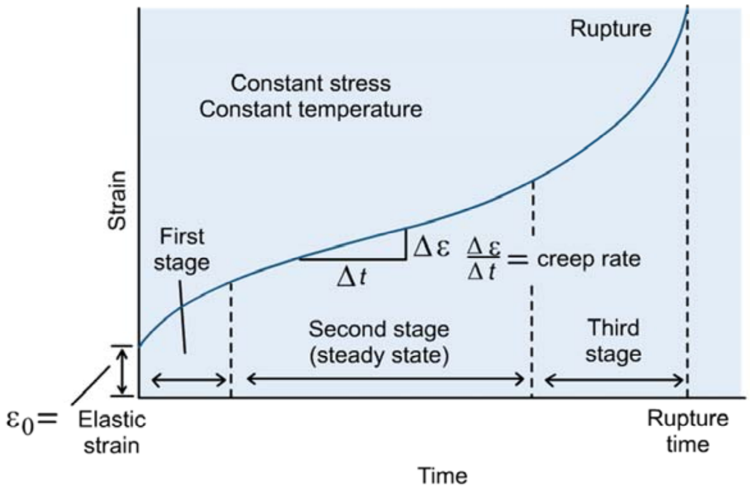
Creep

Creep is the permanent deformation of a material under load as a function of time. It is also known as *static fatigue*.



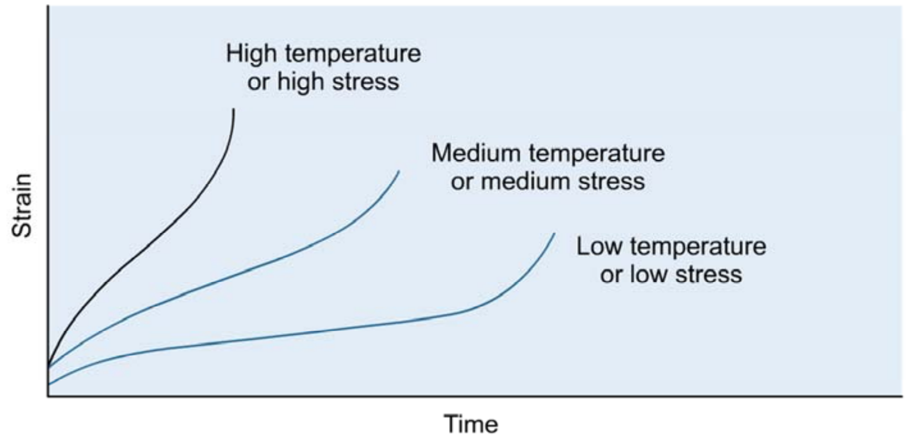
Creep

- In a typical creep curve, the increase in strain under a constant load or stress is plotted as a function of time (or logarithm of time), at constant temperature.

- The creep curve exhibits three stages: In stage I (primary), the creep rate decreases with time; In stage II (secondary), the creep is a minimum and constant with time; In stage III (tertiary), the creep rate increases with time until fracture occurs.

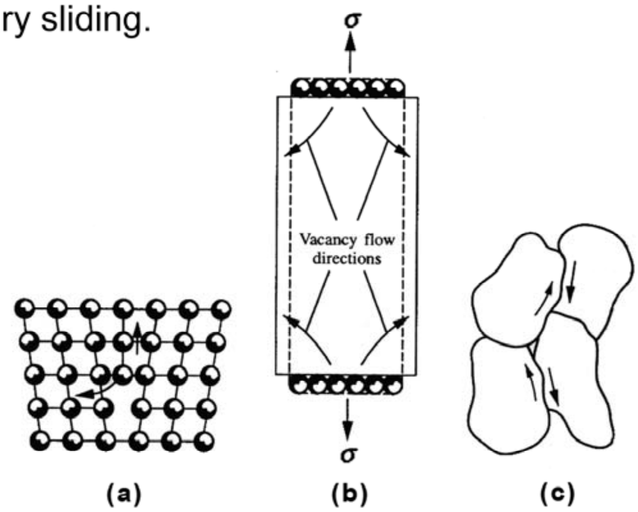
Creep

The temperature and time dependence of creep indicates that it is a *thermally activated process*.



Creep of Metals

The mechanisms of primary creep deformation are (a) dislocation climb, (b) vacancy diffusion and (c) grain boundary sliding.



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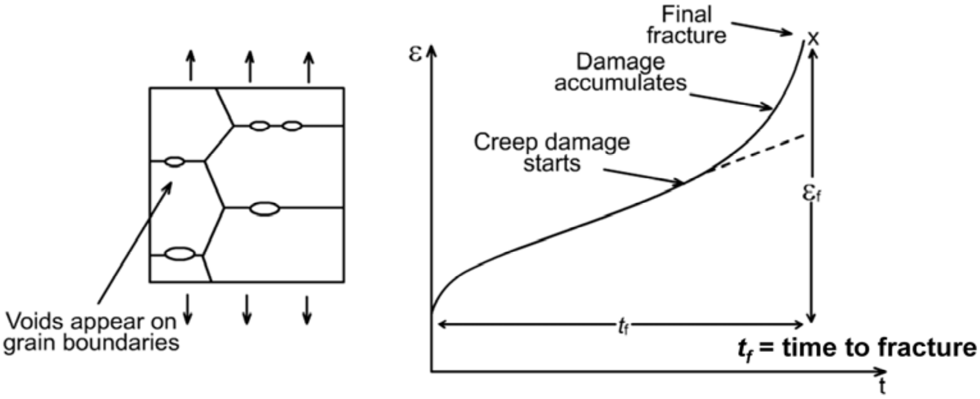
Creep of Metals: Damage and Fracture

At the start of the tertiary stage, damage appears in the form of internal cavities. This grows at an increasing rate, leading to a decrease in section. This results in higher local stress and an even higher creep rate, until fracture occurs.

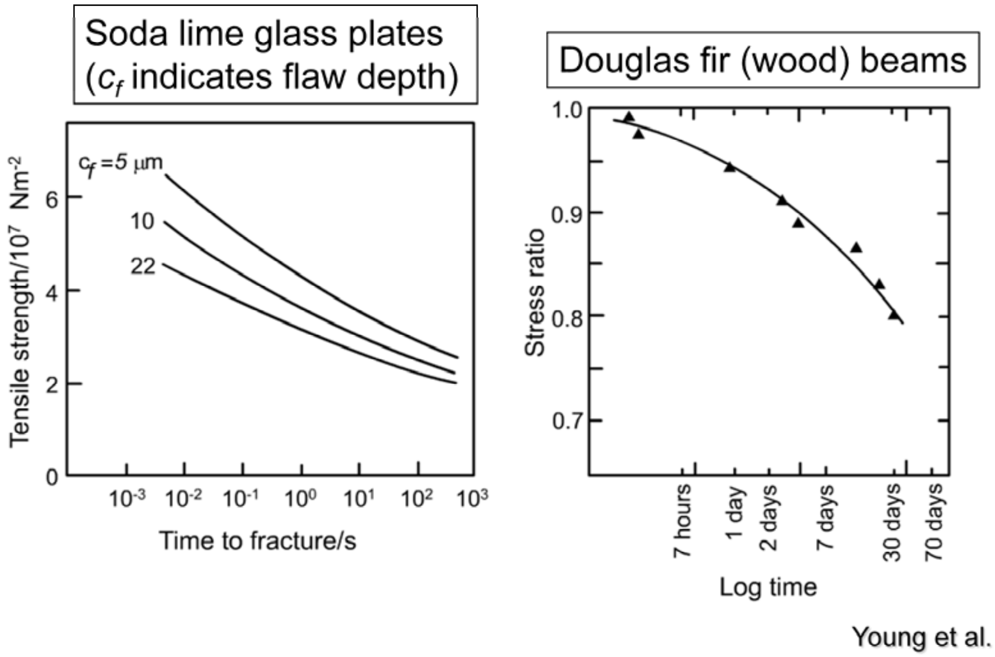


Ashby and Jones

Creep of Other Materials

Materials such as ceramics, concrete, glass and wood can also fail under sustained stresses that are significantly lower than the stresses required to cause failure in conventional (quasi-static) strength tests.

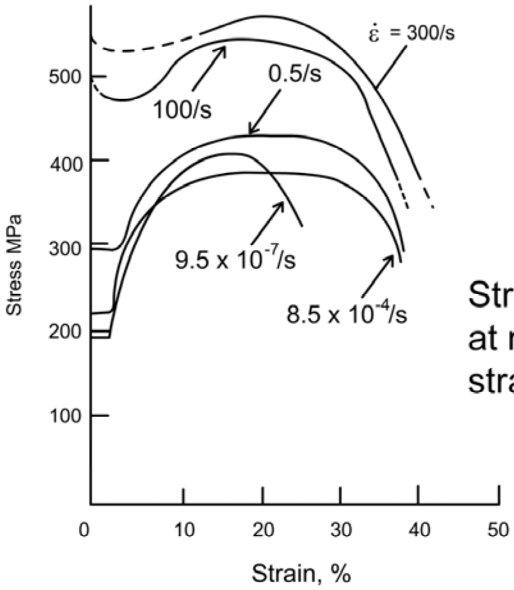
Creep of Other Materials



Effect of Loading Rate

- In general, the tensile strength of a material is higher at higher loading rates.
- For metals, an increase in the strain rate increases the yield strength and raises the stress-strain curve. Metals with a BCC structure are more sensitive to strain rate than FCC metals.

Effect of Loading Rate



Stress-strain curves of mild steel at room temperature for various strain rates

Young et al.

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