

Mechanical Metallurgy

Lecture Summary MT 404, 4th SEM, 2020
MME, NIFFT

Mechanical Metallurgy

Mechanical Properties of Metals

How do metals respond to external loads?

- **Stress and Strain**

- Tension
- Compression
- Shear
- Torsion

- **Elastic deformation**

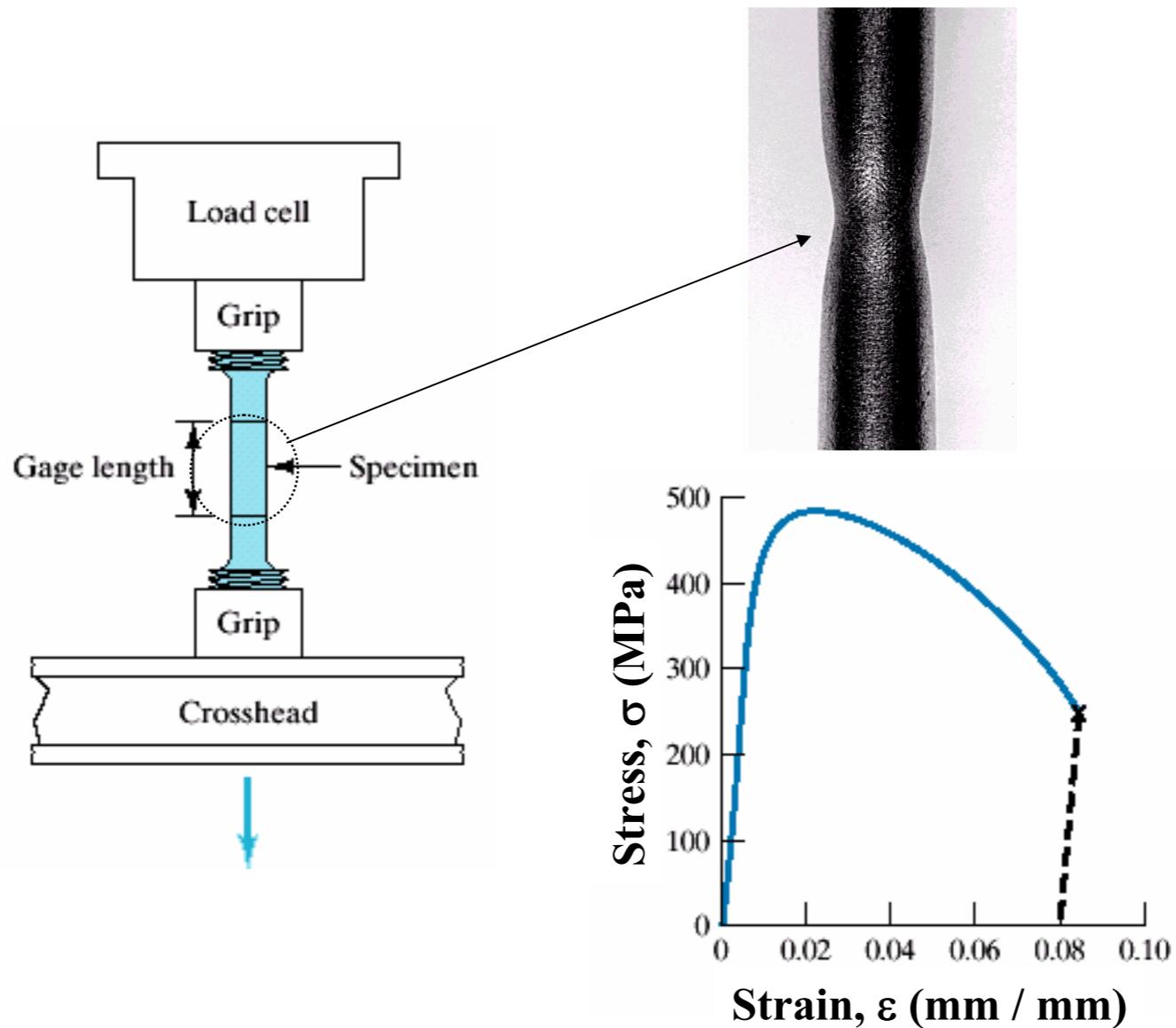
- **Plastic Deformation**

- Yield Strength
- Tensile Strength
- Ductility
- Toughness
- Hardness

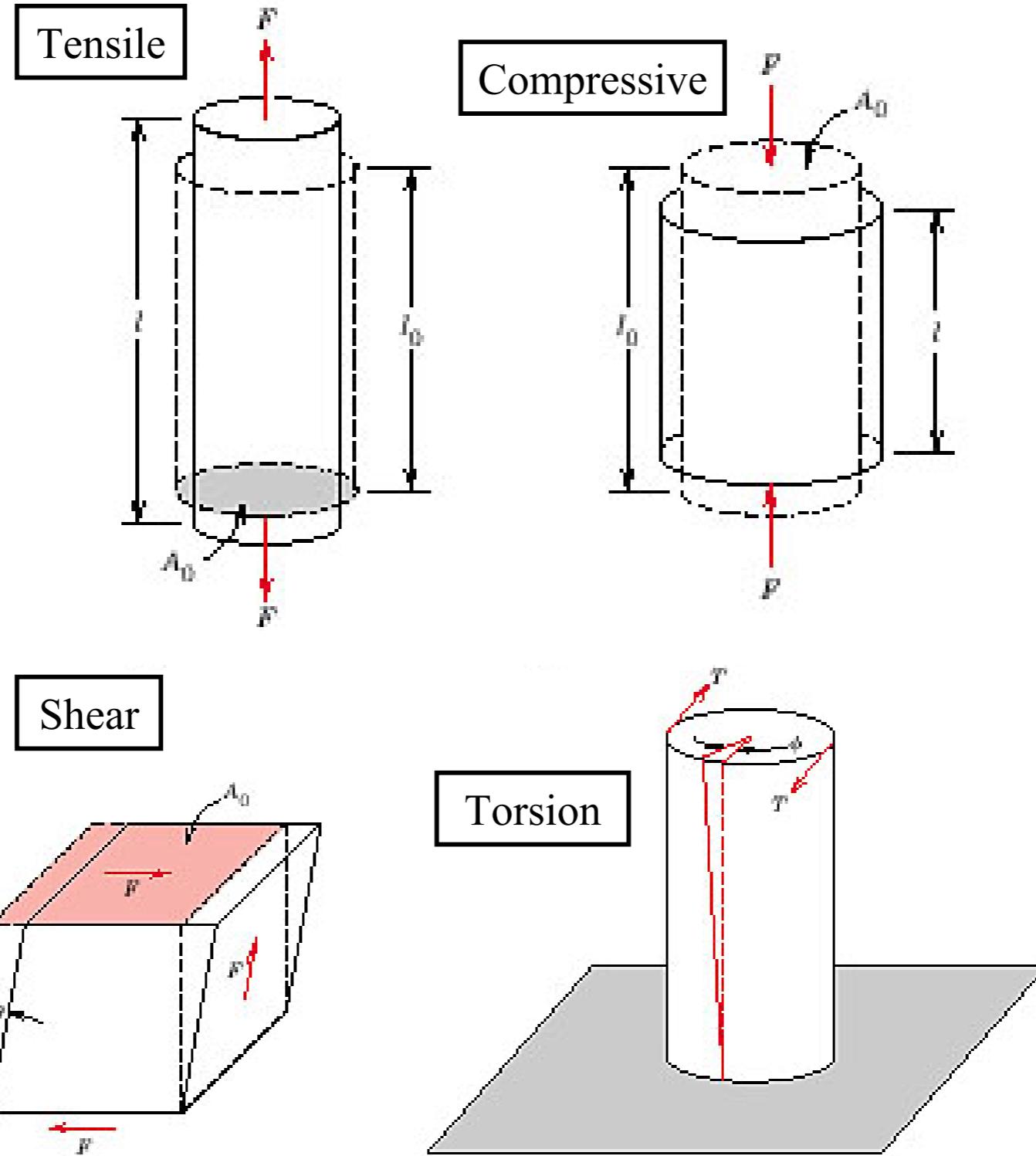
Optional reading (not tested): *details of the different types of hardness tests, variability of material properties* (starting from the middle of page 174)

Introduction

To understand and describe how materials deform (elongate, compress, twist) or break as a function of applied load, time, temperature, and other conditions we need first to discuss standard test methods and standard language for mechanical properties of materials.



Types of loading



Concept of stress and strain (tension and compression)

To compare specimens of different sizes, the load is calculated per unit area.

Engineering stress: $\sigma = F / A_0$

F is load applied perpendicular to specimen cross-section; A_0 is cross-sectional area (perpendicular to the force) **before** application of the load.

Engineering strain: $\varepsilon = \Delta l / l_0 \quad (\times 100 \%)$

Δl is change in length, l_0 is the original length.

These definitions of stress and strain allow one to compare test results for specimens of different cross-sectional area A_0 and of different length l_0 .

Stress and strain are positive for tensile loads, negative for compressive loads

Concept of stress and strain (shear and torsion)

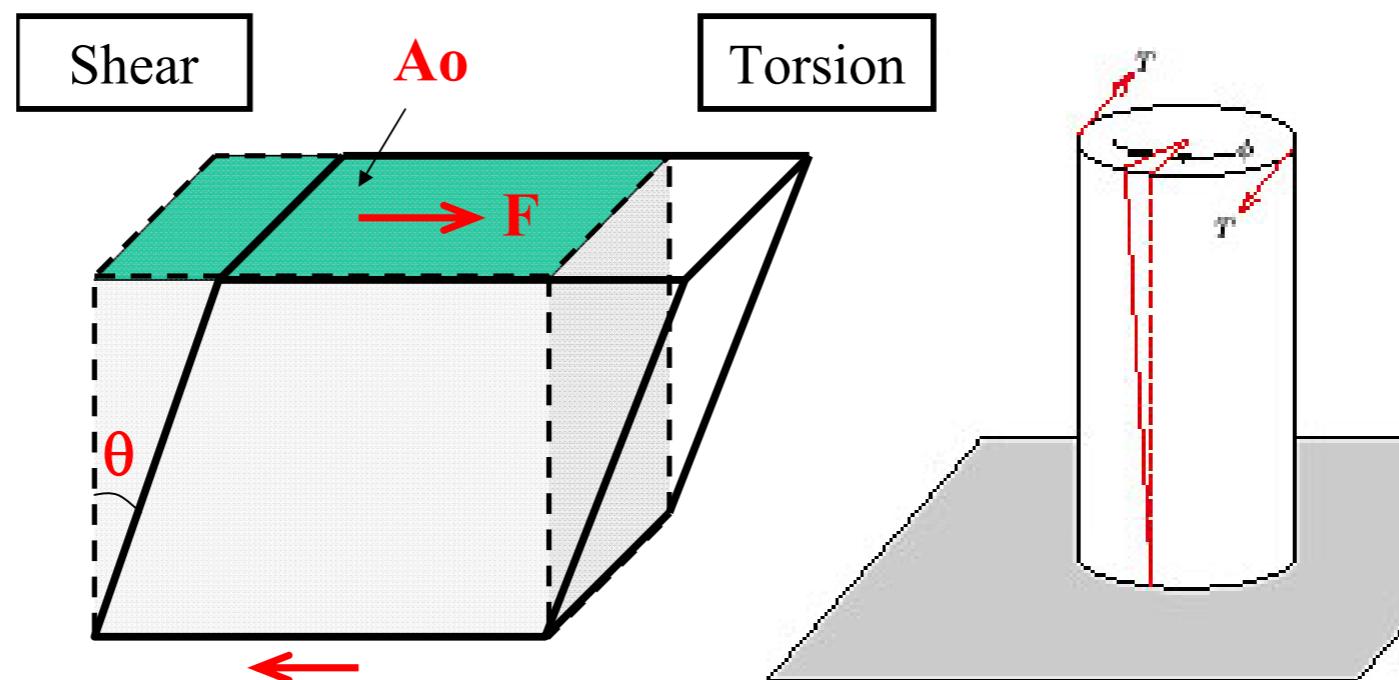
Shear stress: $\tau = F / A_0$

F is load applied parallel to the upper and lower faces each of which has an area A_0 .

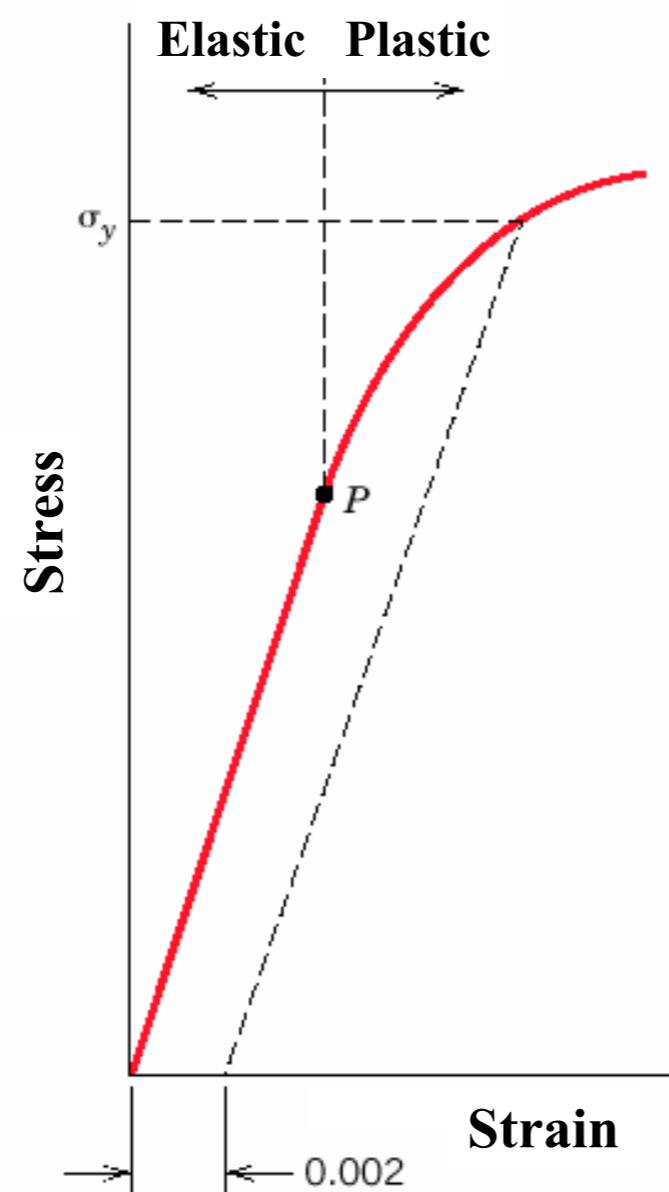
Shear strain: $\gamma = \tan\theta \times 100 \%$

θ is strain angle

Torsion is variation of pure shear. The shear stress in this case is a function of applied torque T, shear strain is related to the angle of twist, ϕ .



Stress-strain behaviour



Elastic deformation

Reversible: when the stress is removed, the material returns to the dimensions it had before the loading.

Usually strains are small (except for the case of some plastics, e.g. rubber).

Plastic deformation

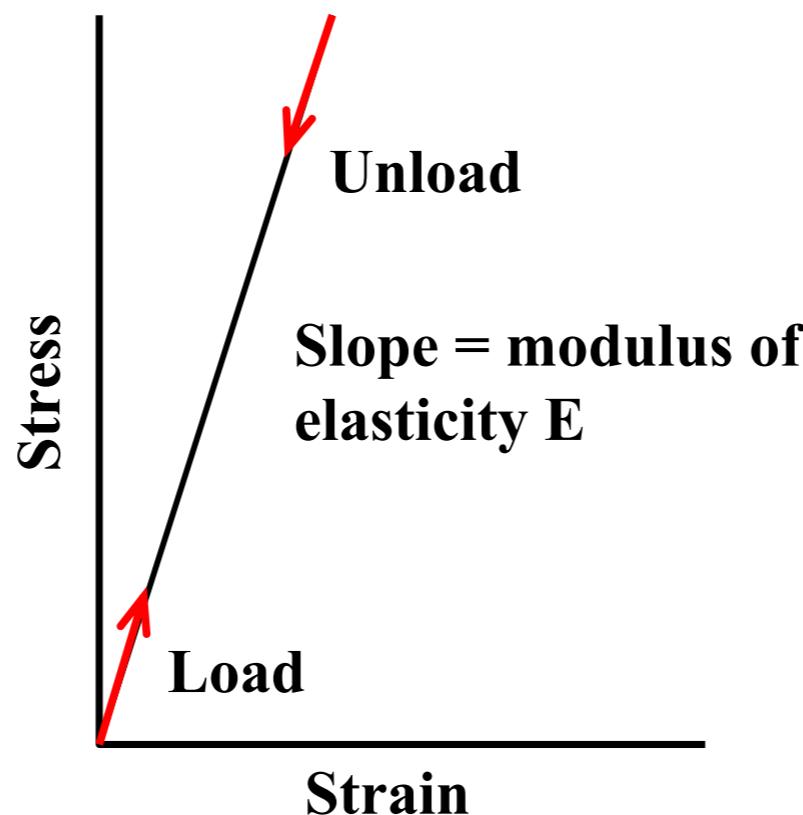
Irreversible: when the stress is removed, the material does not return to its original dimensions.

Stress-strain behaviour: elastic deformation

In tensile tests, if the deformation is elastic, the stress-strain relationship is called [Hooke's law](#):

$$\sigma = E \epsilon$$

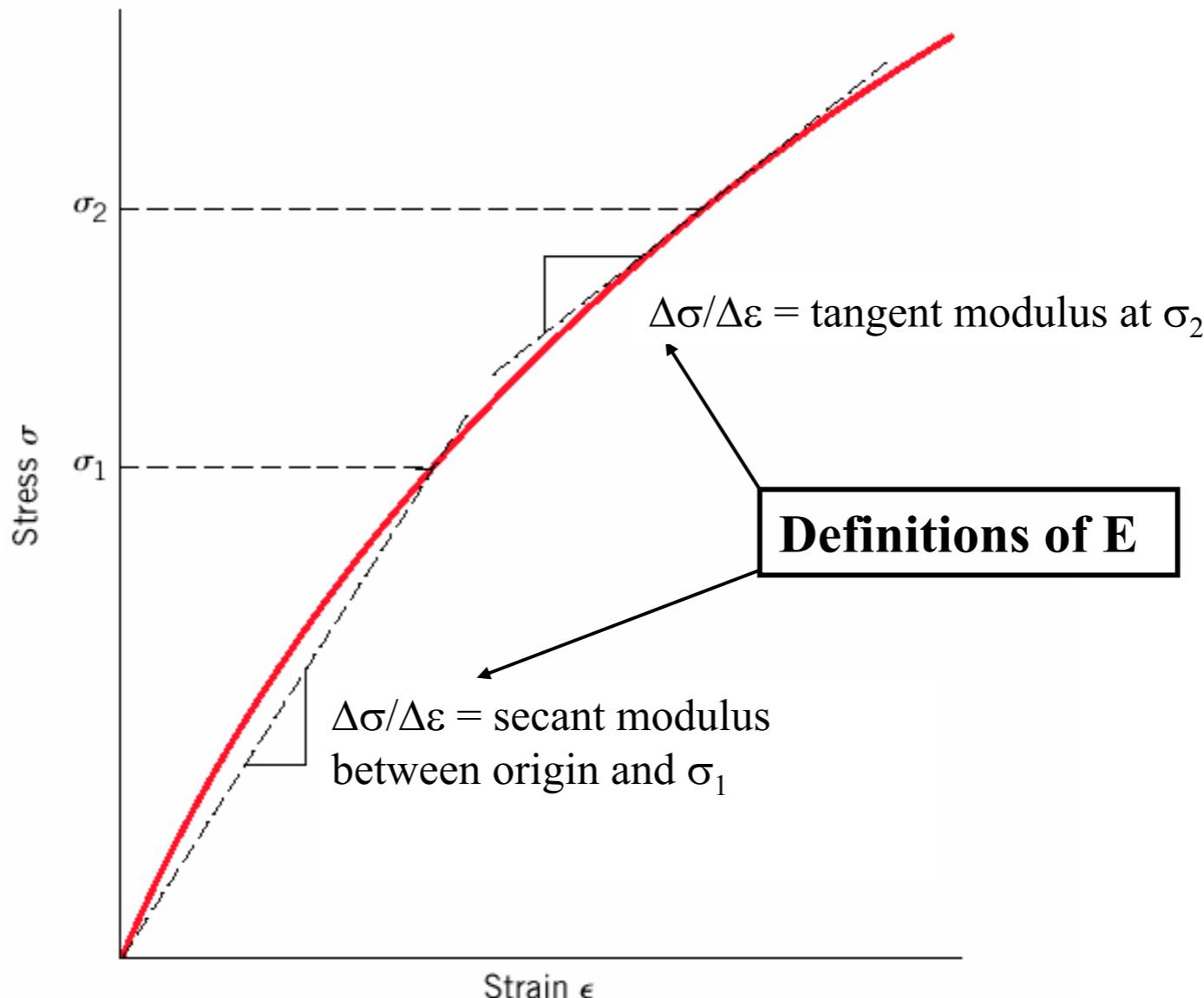
E is [Young's modulus](#) or [modulus of elasticity](#), has the same units as σ , N/m² or Pa



[Higher E → higher “stiffness”](#)

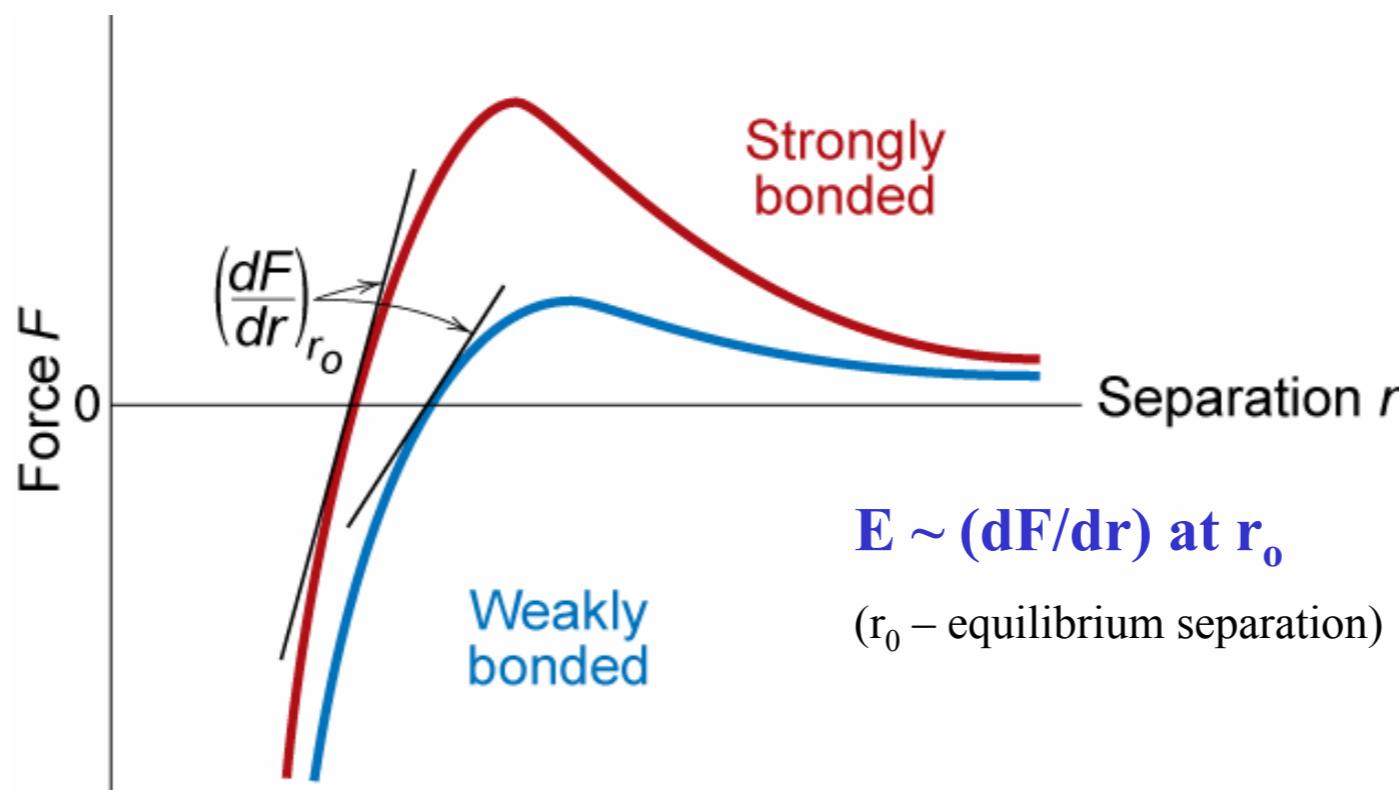
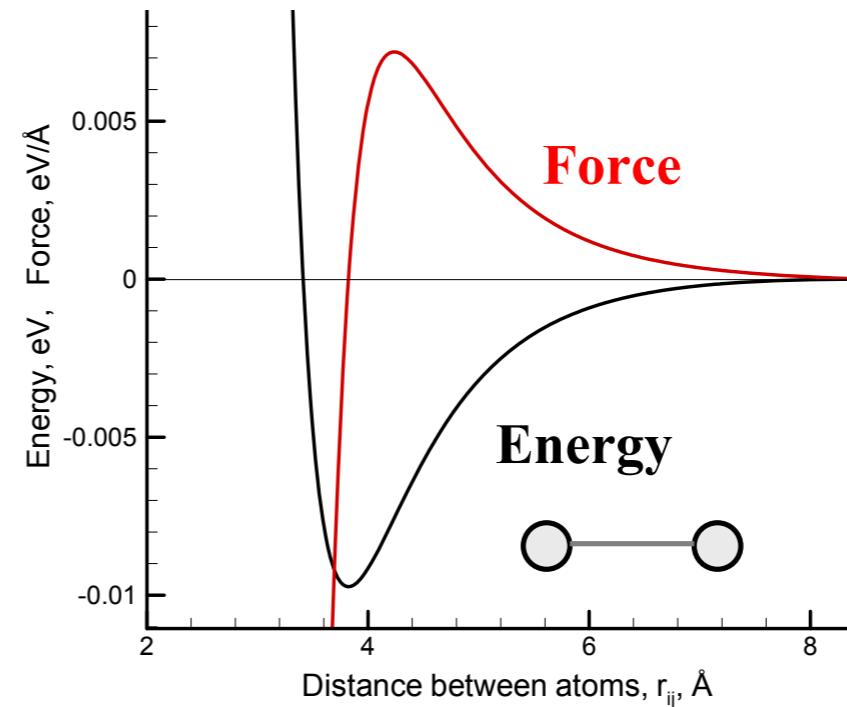
Non-linear elastic behaviour

In some materials (many polymers, concrete...), elastic deformation is not linear, but it is still reversible.



Elastic deformation: atomic scale

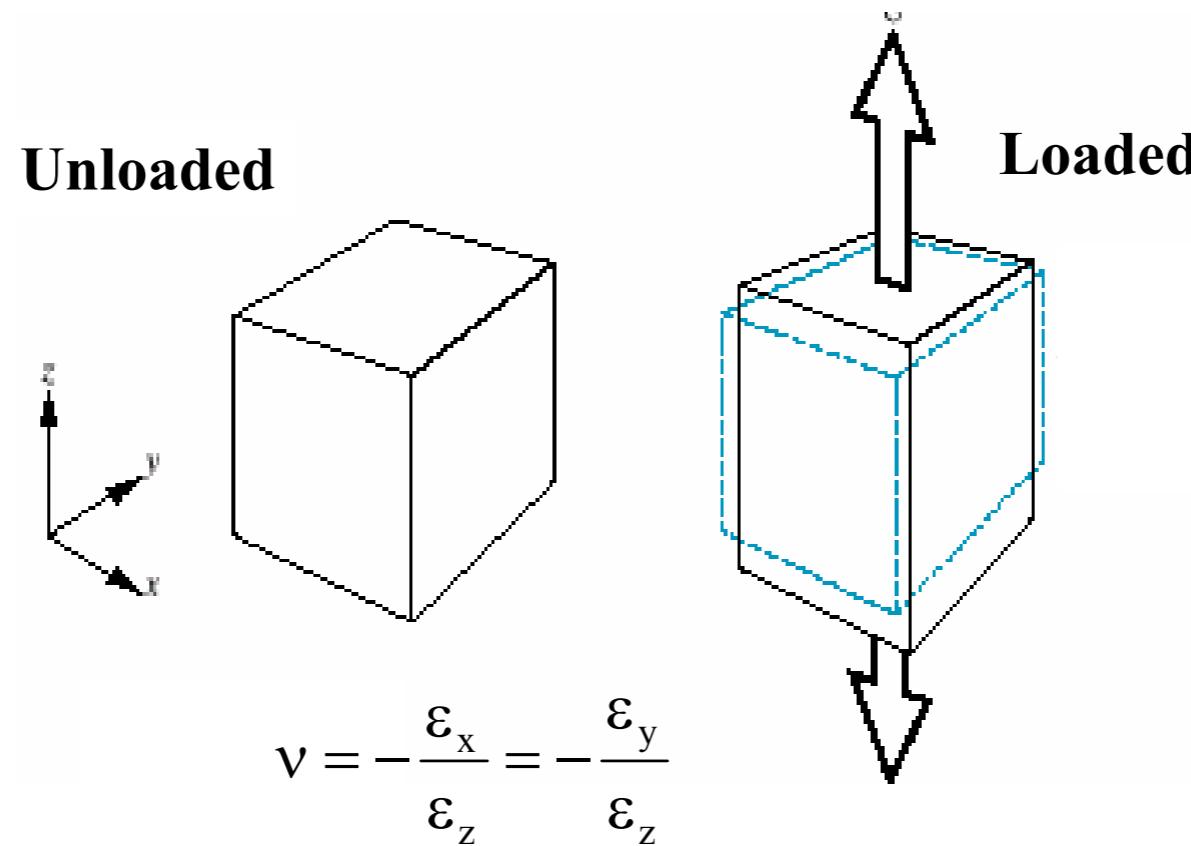
Chapter 2:
force-separation
curve for
interacting atoms



Elastic deformation: anelasticity (time dependent elastic deformation)

- So far we have assumed that elastic deformation is time independent (i.e. applied stress produces instantaneous elastic strain)
- However, in reality elastic deformation takes time (finite rate of atomic/molecular deformation processes) - continues after initial loading, and after load release. This time dependent elastic behavior is known as **anelasticity**.
- The effect is normally small for metals but can be significant for polymers (“**visco-elastic behavior**”).

Elastic deformation: poissons ratio



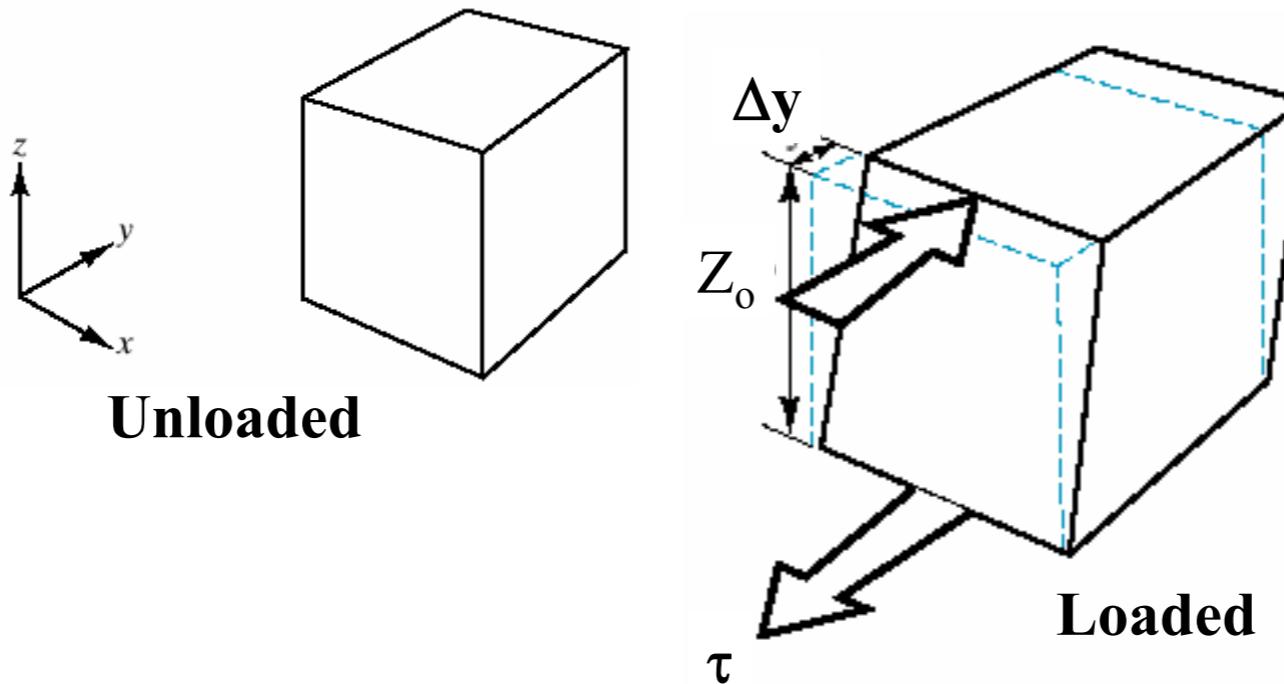
Materials subject to tension shrink laterally. Those subject to compression, bulge. The ratio of lateral and axial strains is called the **Poisson's ratio ν** . Sign in the above equations shows that lateral strain is in opposite sense to longitudinal strain

ν is dimensionless

Theoretical value for isotropic material: 0.25

Maximum value: 0.50, Typical value: 0.24 - 0.30

Elastic deformation: shear modulus



Relationship of shear stress to shear strain:

$$\tau = G \gamma, \text{ where: } \gamma = \tan \theta = \Delta y / Z_0$$

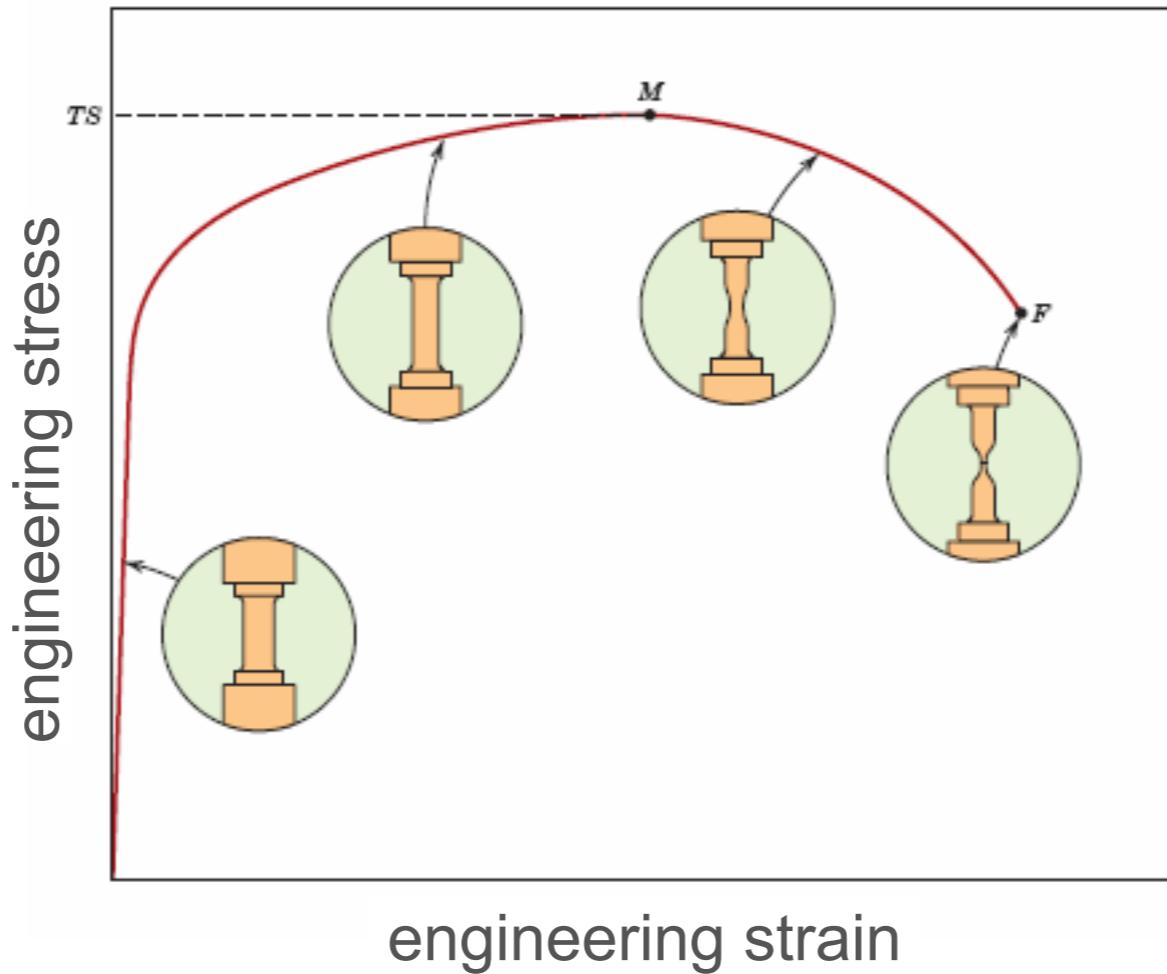
G is Shear Modulus (Units: N/m² or Pa)

For isotropic material:

$$E = 2G(1+\nu) \rightarrow G \sim 0.4E$$

(Note: single crystals are usually elastically anisotropic: the elastic behavior varies with crystallographic direction, see Chapter 3)

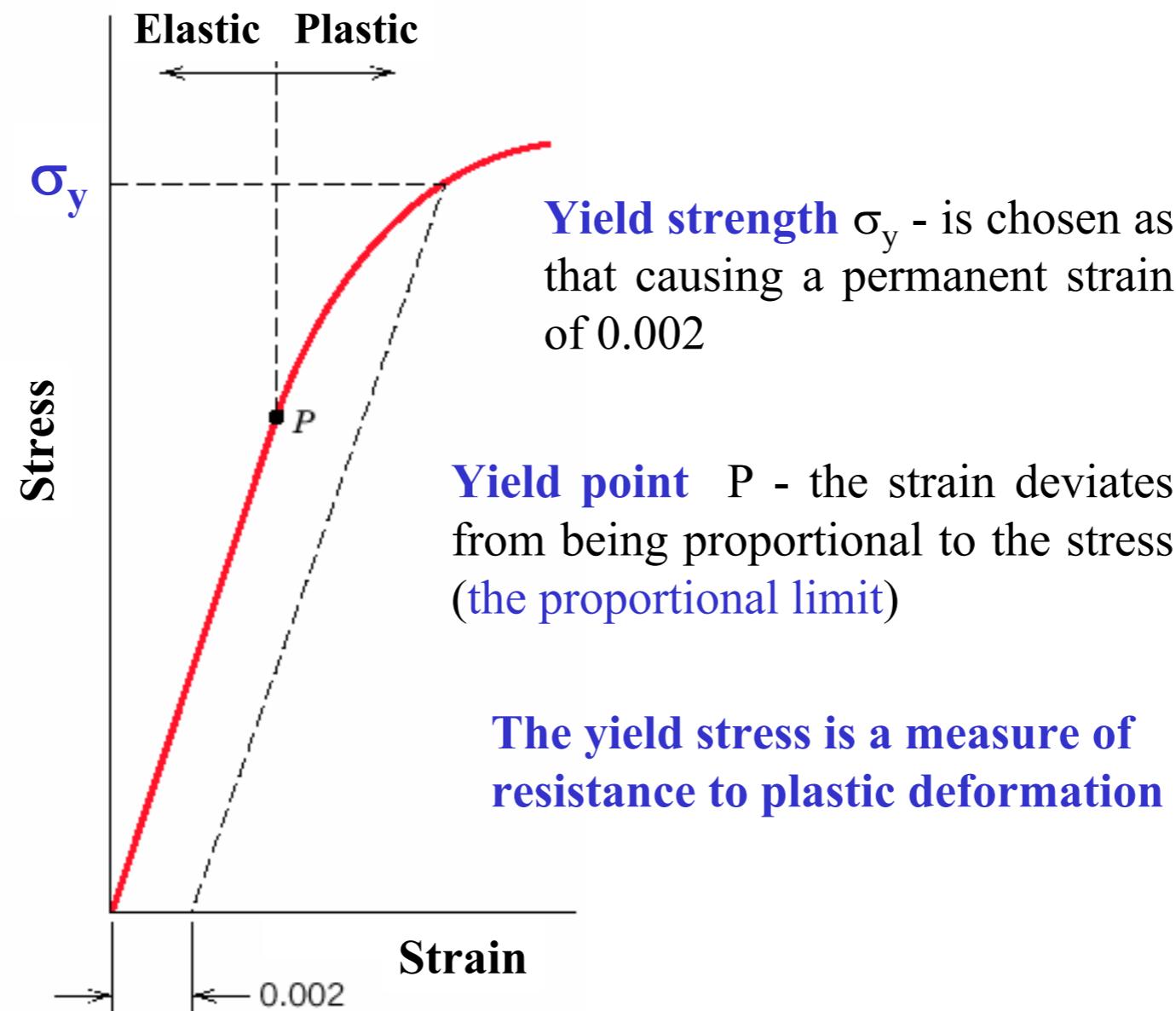
Plastic deformation



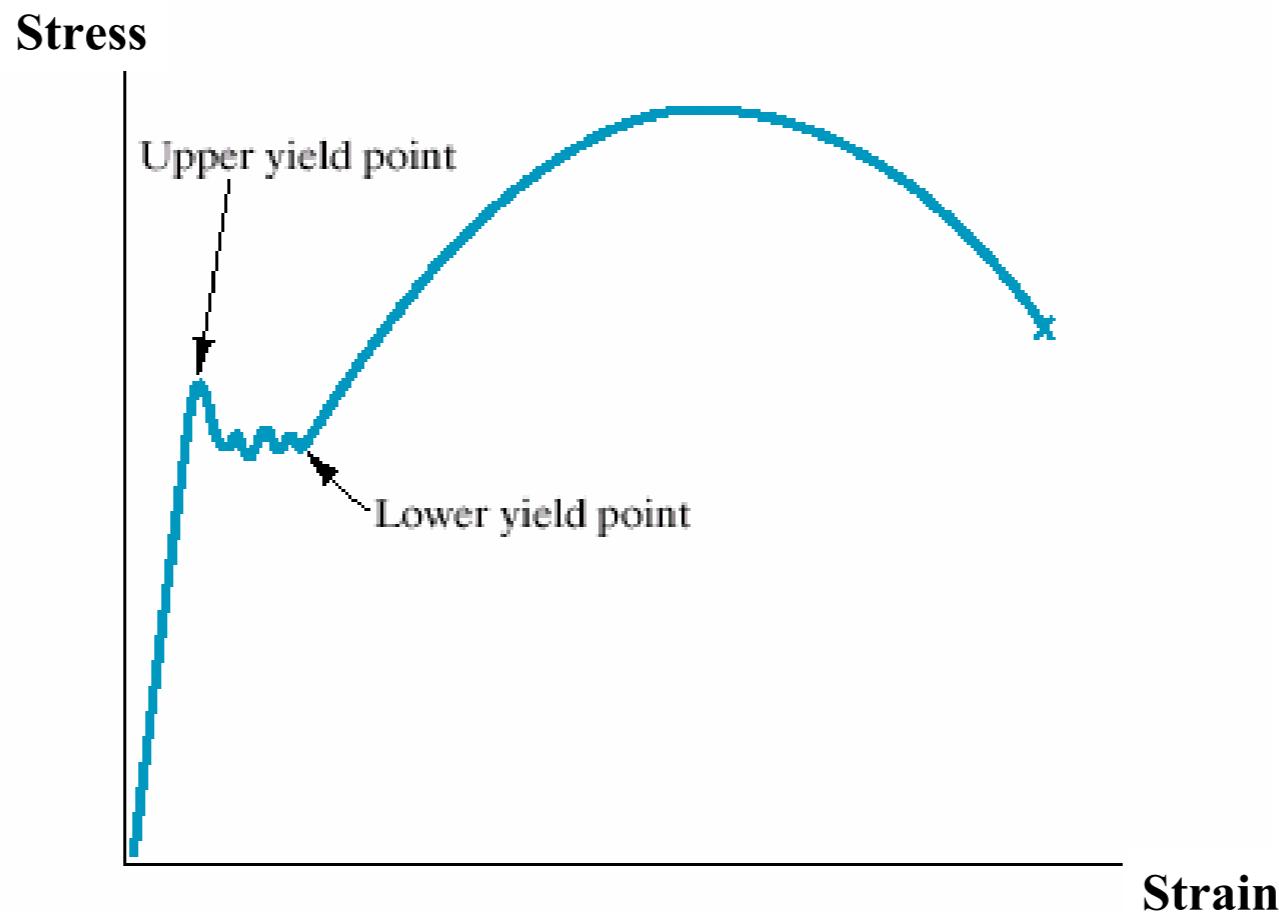
Plastic deformation:

- stress and strain are not proportional to each other
- the deformation is not reversible
- deformation occurs by breaking and re-arrangement of atomic bonds (in crystalline materials primarily by motion of dislocations, Chapter 7)

Tensile properties: yielding



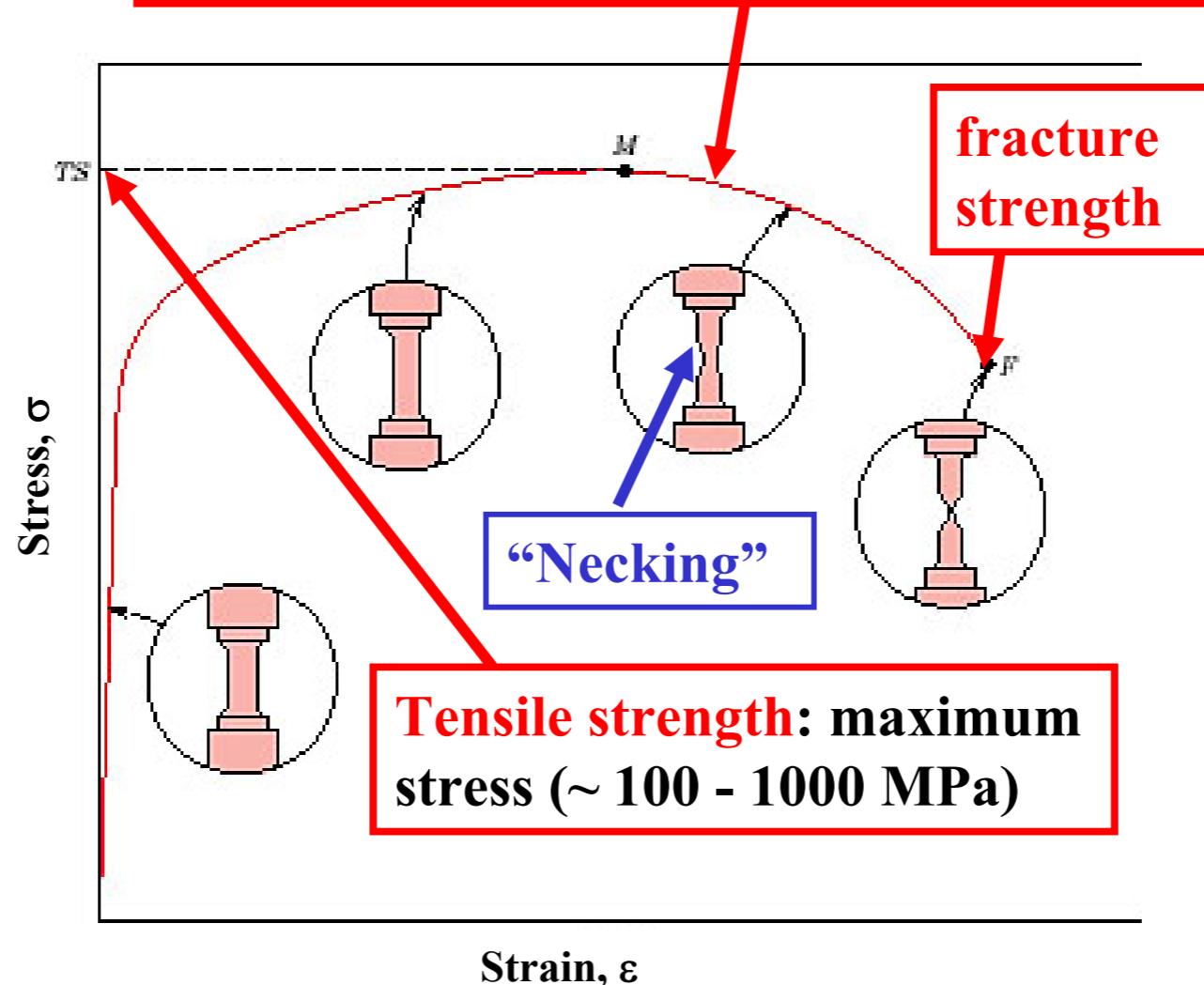
Tensile properties: yielding



In some materials (e.g. low-carbon steel), the stress vs. strain curve includes two yield points (upper and lower). The yield strength is defined in this case as the average stress at the lower yield point.

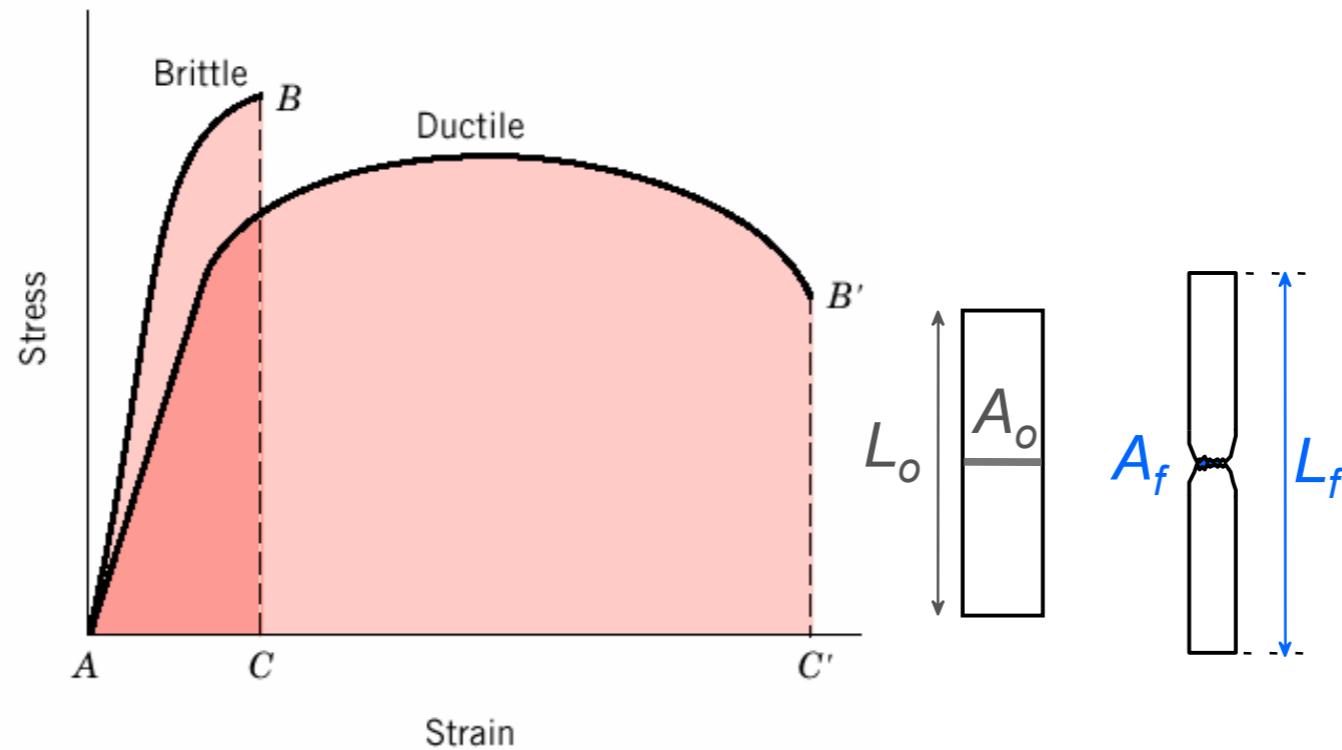
Tensile strength

If stress = **tensile strength** is maintained
then specimen will eventually break



For structural applications, the yield stress is usually a more important property than the tensile strength, since once the yield stress has passed, the structure has deformed beyond acceptable limits.

Tensile properties: ductility



Ductility is a measure of the deformation at fracture

Defined by percent elongation $\%EL = \left(\frac{l_f - l_0}{l_0} \right) \times 100$
(plastic tensile strain at failure)

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

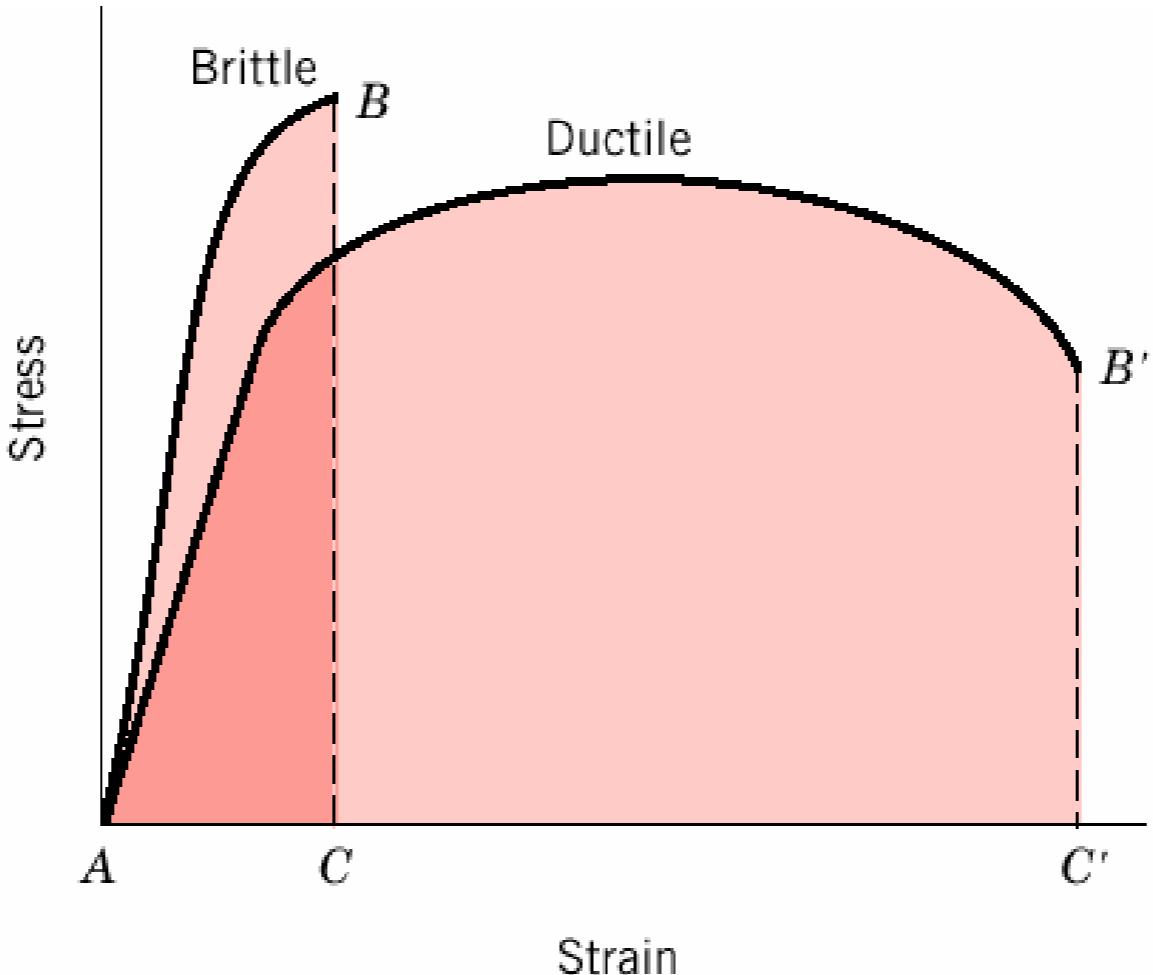
Typical mechanical properties of Materials

<i>Metal Alloy</i>	<i>Yield Strength MPa (ksi)</i>	<i>Tensile Strength MPa (ksi)</i>	<i>Ductility, %EL [in 50 mm (2 in.)]</i>
Aluminum	35 (5)	90 (13)	40
Copper	69 (10)	200 (29)	45
Brass (70Cu–30Zn)	75 (11)	300 (44)	68
Iron	130 (19)	262 (38)	45
Nickel	138 (20)	480 (70)	40
Steel (1020)	180 (26)	380 (55)	25
Titanium	450 (65)	520 (75)	25
Molybdenum	565 (82)	655 (95)	35

The yield strength and tensile strength vary with prior thermal and mechanical treatment, impurity levels, etc. This variability is related to the behavior of dislocations in the material, Chapter 7. But elastic moduli are relatively insensitive to these effects.

The yield and tensile strengths and modulus of elasticity decrease with increasing temperature, ductility increases with temperature.

Toughness



Toughness = the ability to absorb energy up to fracture = the total area under the strain-stress curve up to fracture

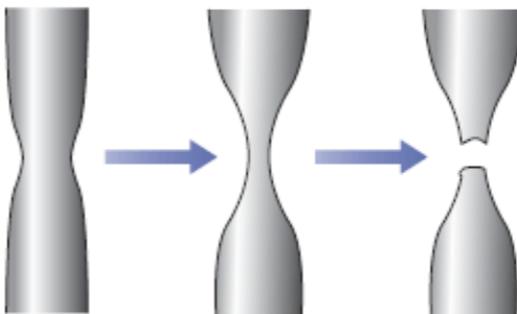
$$\int_0^{\varepsilon_f} \sigma d\varepsilon$$

Units: the energy per unit volume, e.g. J/m³

Can be measured by an impact test (Chapter 8).

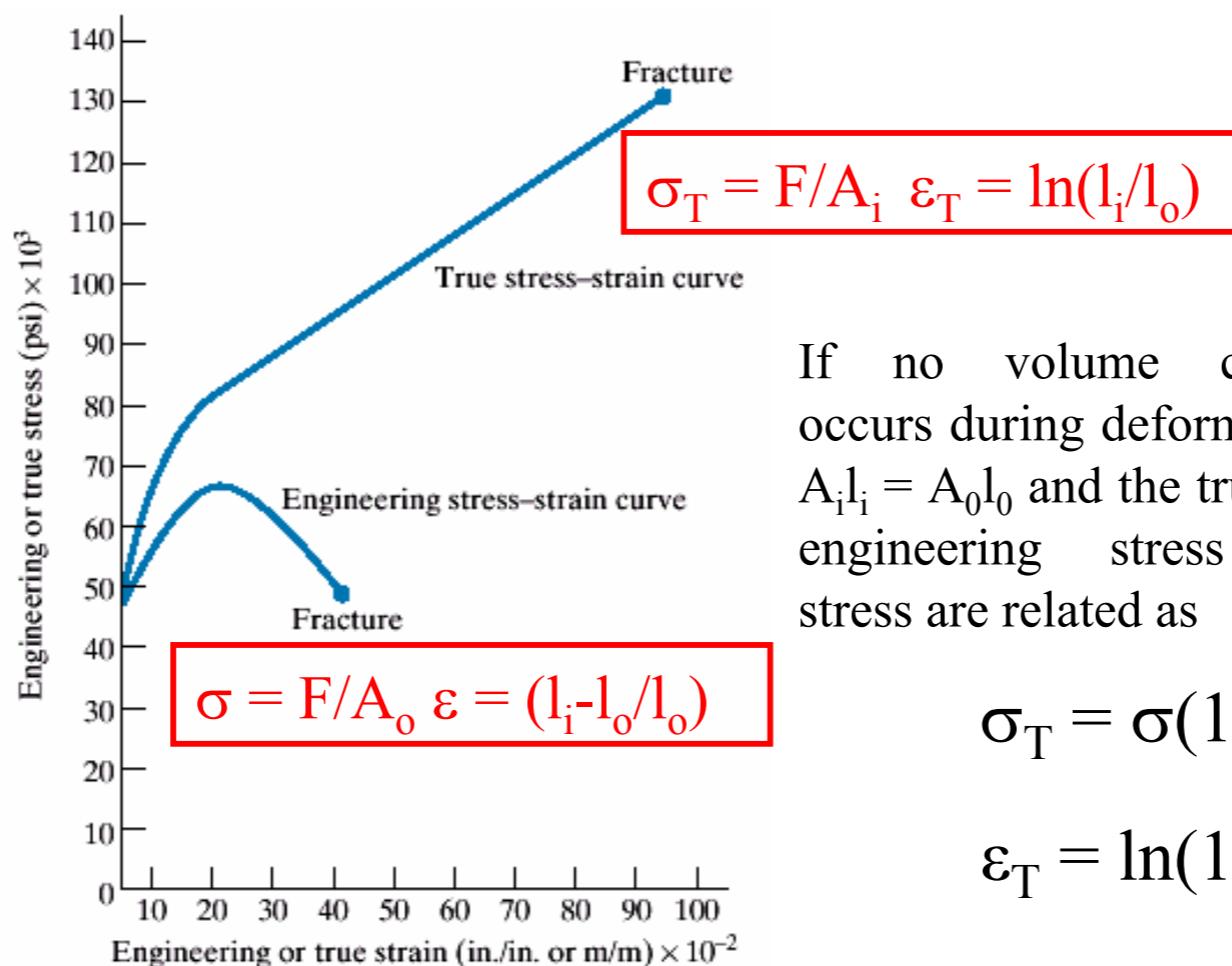
True stress-strain

True stress = load divided by **actual area** in the necked-down region (A_i): $\sigma_T = F/A_i$



Sometimes it is convenient to use **true strain** defined as $\epsilon_T = \ln(l_i/l_o)$

True stress continues to rise to the point of fracture, in contrast to the engineering stress.

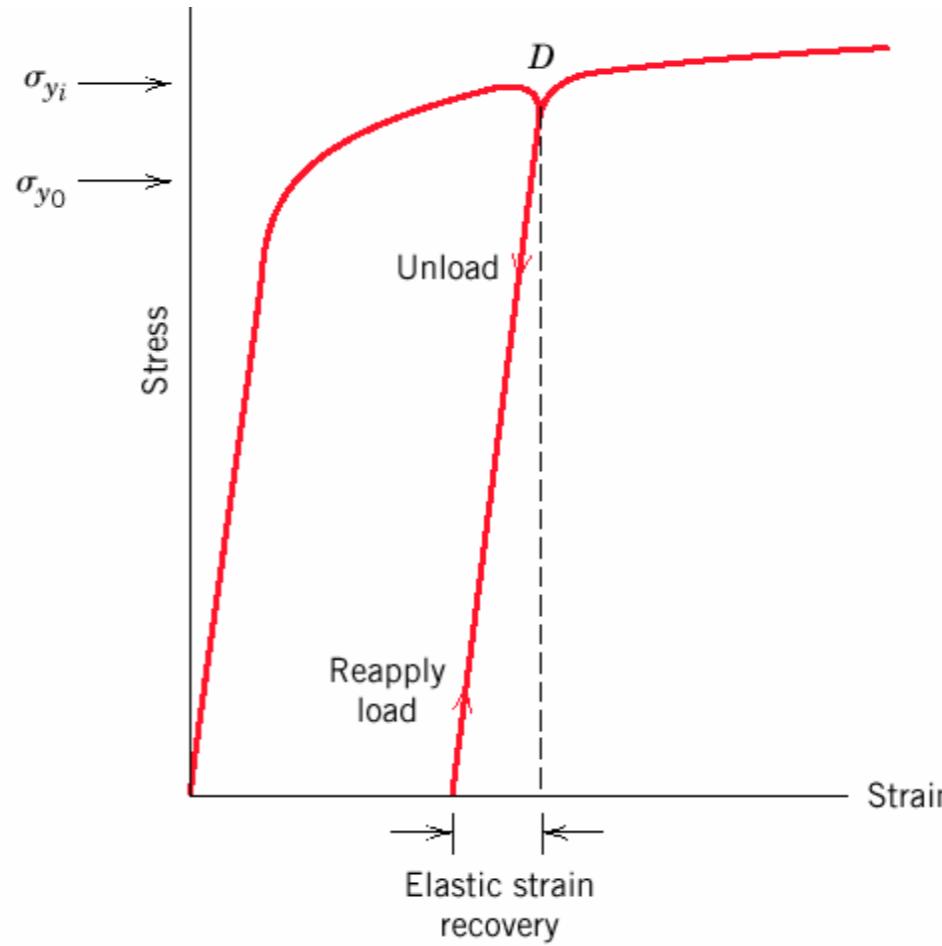


If no volume change occurs during deformation, $A_i l_i = A_0 l_0$ and the true and engineering stress and strain are related as

$$\sigma_T = \sigma(1 + \epsilon)$$

$$\epsilon_T = \ln(1 + \epsilon)$$

Elastic recovery during plastic deformation



If a material is deformed plastically and the stress is then released, the material ends up with a permanent strain.

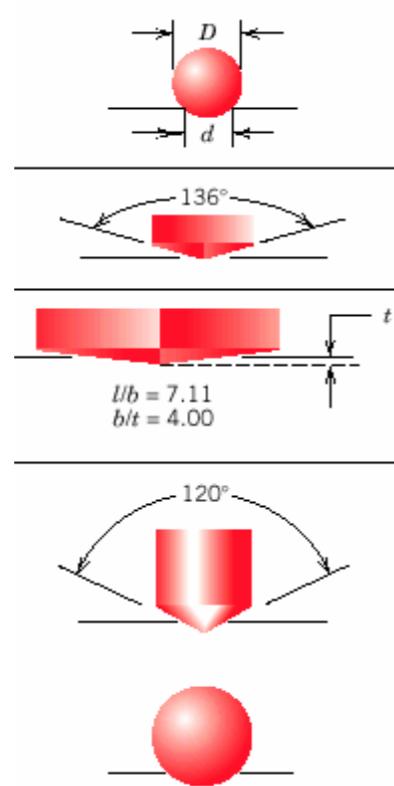
If the stress is reapplied, the material again responds elastically at the beginning up to a new yield point that is **higher than the original yield point**.

The amount of elastic strain that it will take before reaching the yield point is called **elastic strain recovery**.

Hardness

Hardness is a measure of the material's resistance to localized plastic deformation (e.g. dent or scratch)

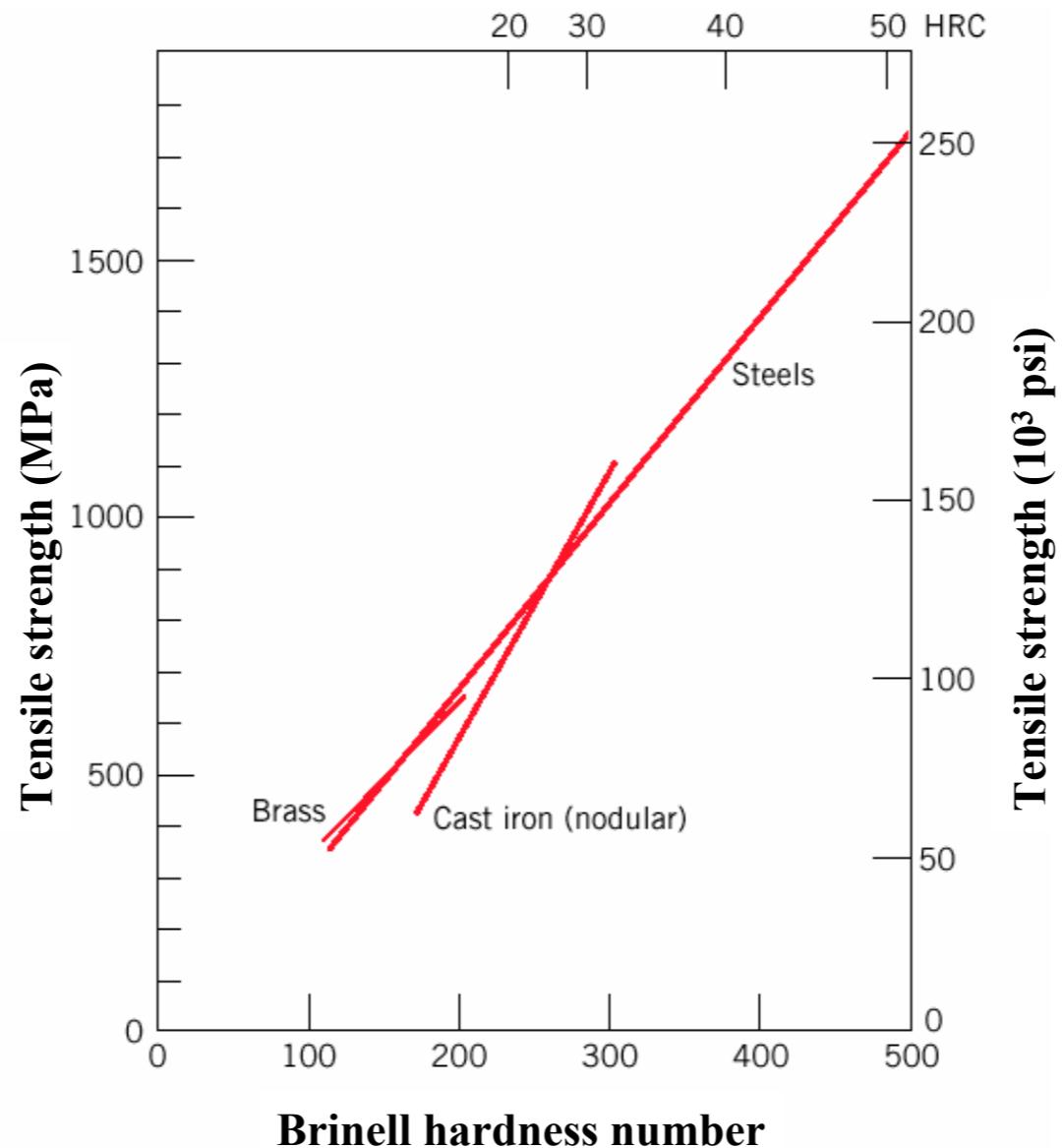
A qualitative Moh's scale, determined by the ability of a material to scratch another material: from 1 (softest = talc) to 10 (hardest = diamond).



Different types of quantitative hardness test have been designed (Rockwell, Brinell, Vickers, etc.). Usually a small indenter (sphere, cone, or pyramid) is forced into the surface of a material under conditions of controlled magnitude and rate of loading. The depth or size of indentation is measured.

The tests somewhat approximate, but popular because they are easy and non-destructive (except for the small dent).

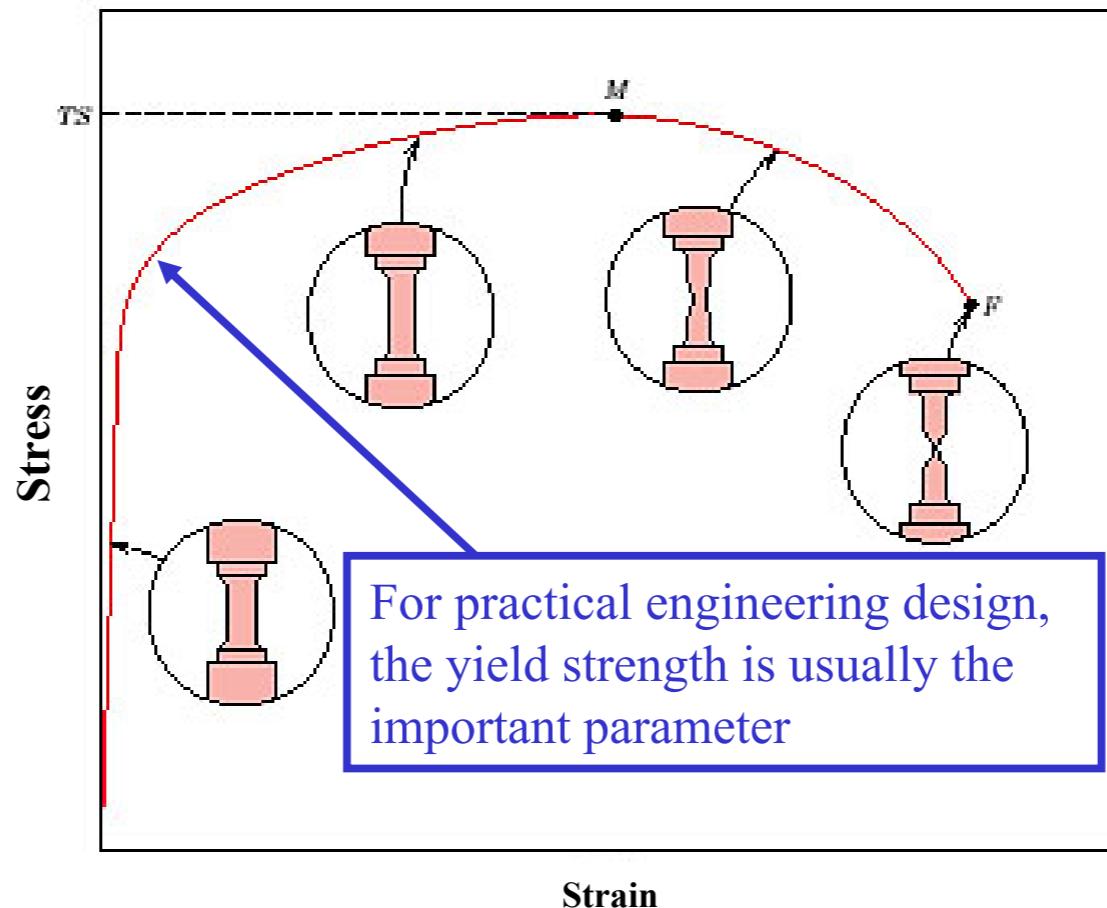
Hardness-II



Both tensile strength and hardness may be regarded as degree of resistance to plastic deformation.

Hardness is proportional to the tensile strength - but note that the proportionality constant is different for different materials.

Limits of safe deformation



Design stress: $\sigma_d = N' \sigma_c$ where σ_c = maximum anticipated stress, N' is the “design factor” > 1 . Want to make sure that $\sigma_d < \sigma_y$

Safe or working stress: $\sigma_w = \sigma_y/N$ where N is “factor of safety” > 1 .

Summary

- **Stress** and **strain**: Size-independent measures of load and displacement, respectively.
- **Elastic** behavior: Reversible mechanical deformation, often shows a linear relation between stress and strain.
- Elastic deformation is characterized by **elastic moduli** (E or G). To minimize deformation, select a material with a large elastic moduli (E or G).
- **Plastic** behavior: Permanent deformation, occurs when the tensile (or compressive) uniaxial stress reaches the **yield strength** σ_y .
- **Tensile strength**: maximum stress supported by the material.
- **Toughness**: The energy needed to break a unit volume of material.
- **Ductility**: The plastic strain at failure.

Dislocation Theory and strengthening of Materials

Dislocation Theory and strengthening of Materials

Dislocations and Strengthening Mechanisms

What is happening in material during plastic deformation?

- **Dislocations and Plastic Deformation**

- ✓ Motion of dislocations in response to stress
- ✓ Slip Systems
- ✓ Plastic deformation in
 - single crystals
 - polycrystalline materials

- **Strengthening mechanisms**

- ✓ Grain Size Reduction
- ✓ Solid Solution Strengthening
- ✓ Strain Hardening

- **Recovery, Recrystallization, and Grain Growth**

Not tested: 7.7 Deformation by twinning,

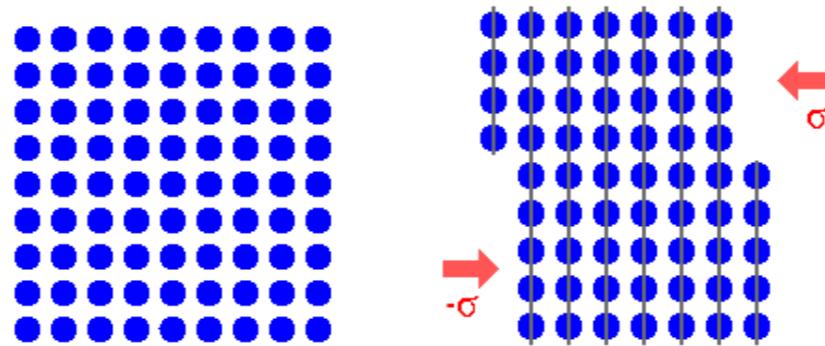
Direction and plane nomenclature in §7.4.

Introduction

Why metals could be plastically deformed?

Why the plastic deformation properties could be changed to a very large degree by forging without changing the chemical composition?

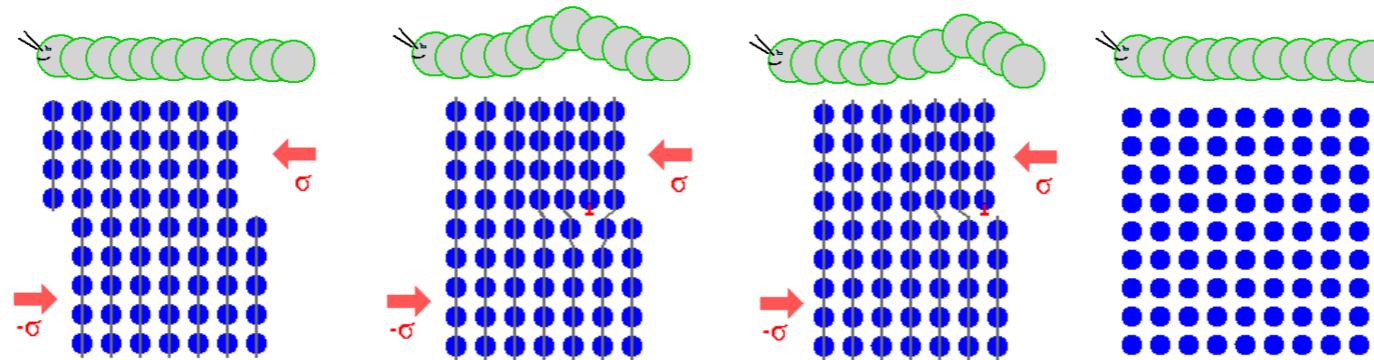
Why plastic deformation occurs at stresses that are much smaller than the theoretical strength of perfect crystals?



Plastic deformation – the force to break all bonds in the slip plane is much higher than the force needed to cause the deformation. Why?

These questions can be answered based on the idea proposed in 1934 by Taylor, Orowan and Polyani: **Plastic deformation is due to the motion of a large number of dislocations.**

Dislocation allow deformation at much lower stress than in a perfect crystal

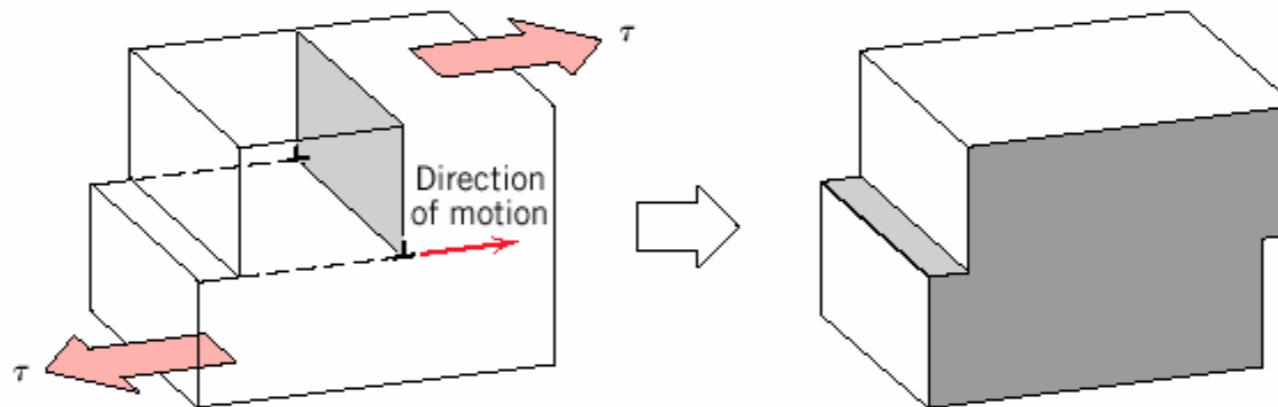


If the top half of the crystal is slipping one plane at a time then only a small fraction of the bonds are broken at any given time and this would require a much smaller force.

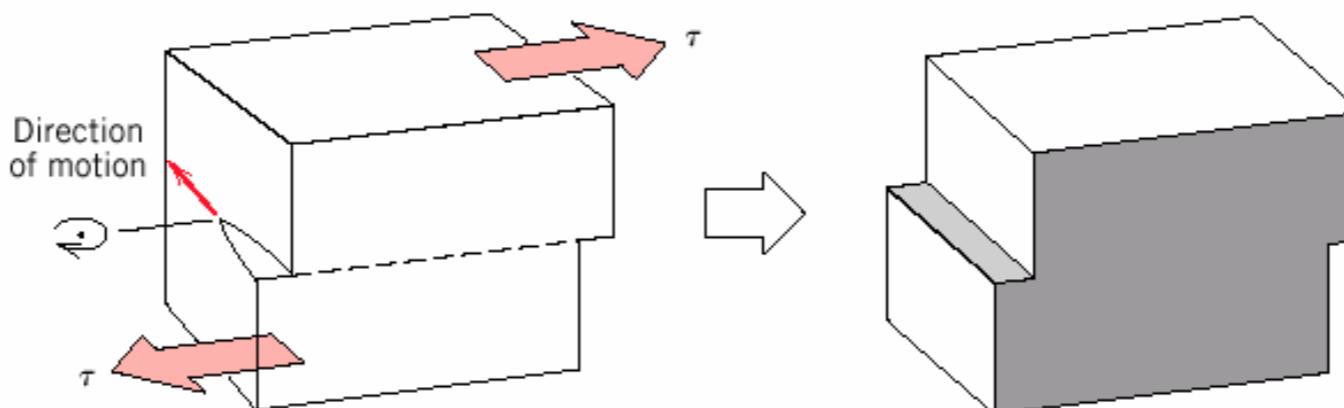
The propagation of one dislocation across the plane causes the top half of the crystal to move (**to slip**) with respect to the bottom half but we do not have to break all the bonds across the middle plane simultaneously (which would require a very large force).

The slip plane – the crystallographic plane of dislocation motion.

Direction of dislocation motion



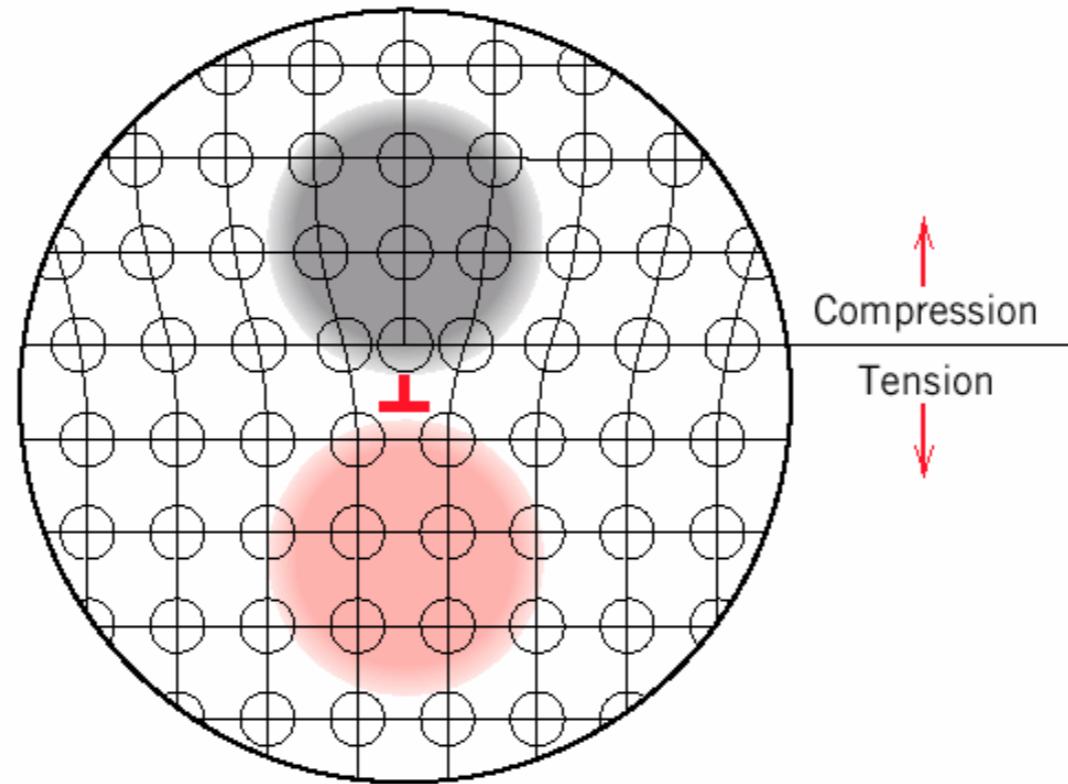
Edge dislocation line moves parallel to applied stress



Screw dislocation line moves perpendicular to applied stress

For mixed dislocations, direction of motion is in between parallel and perpendicular to the applied shear stress

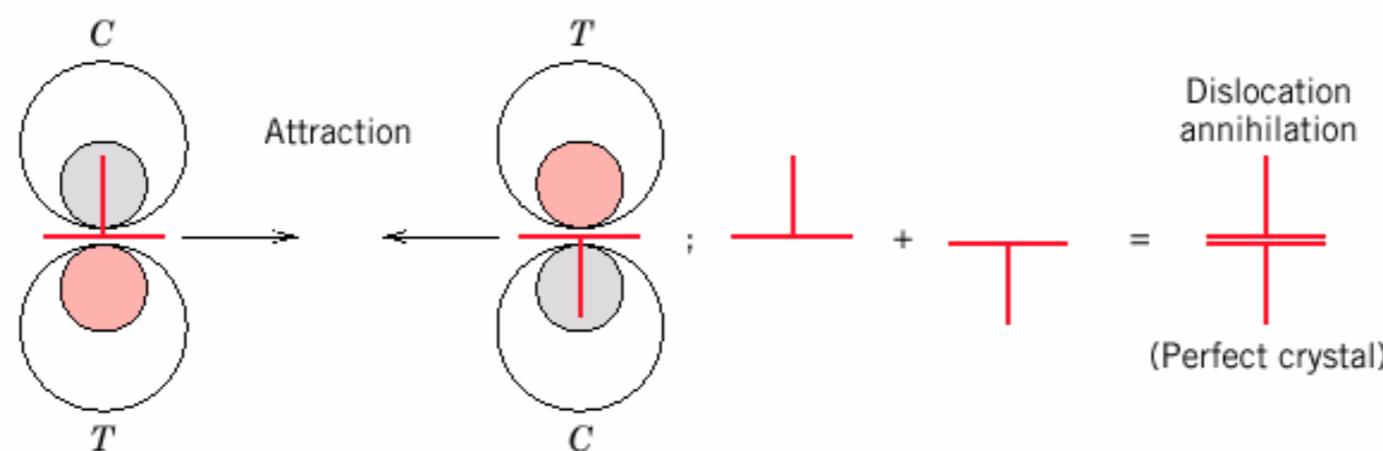
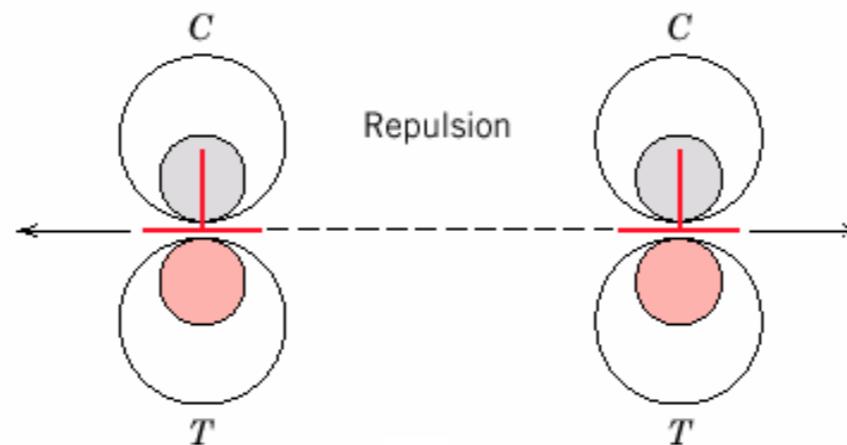
Strain field around dislocation



Dislocations have strain fields arising from distortions at their cores - strain drops radially with distance from the dislocation core

Edge dislocations introduce compressive, tensile, and shear lattice strains, screw dislocations introduce shear strain only.

Interaction between dislocations-I



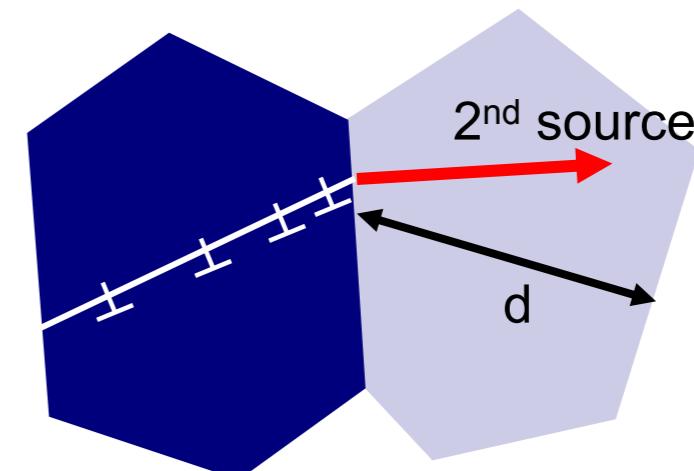
The strain fields around dislocations cause them to **interact** (exert force on each other). When they are in the same plane, they repel if they have the same sign (direction of the Burgers vector) and attract/annihilate if they have opposite signs.

Interaction between dislocations-II

DISLOCATION INTERACTIONS

- Dislocations reduce the stress required to plastically deform materials
- Dislocations interact with
 - Forests of Dislocations
 - Grain Boundaries
 - Hall - Petch Relationship
 - Precipitates
 - Solutes

$$\tau_y \propto \frac{1}{\sqrt{d}}$$



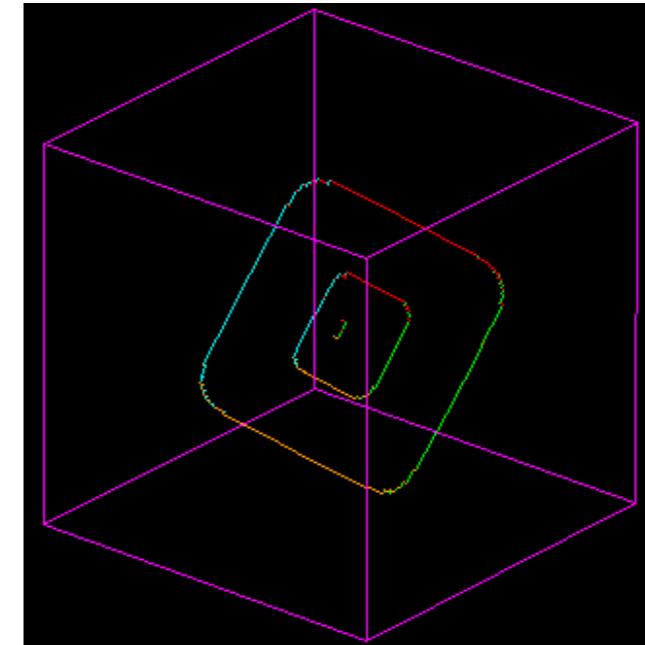
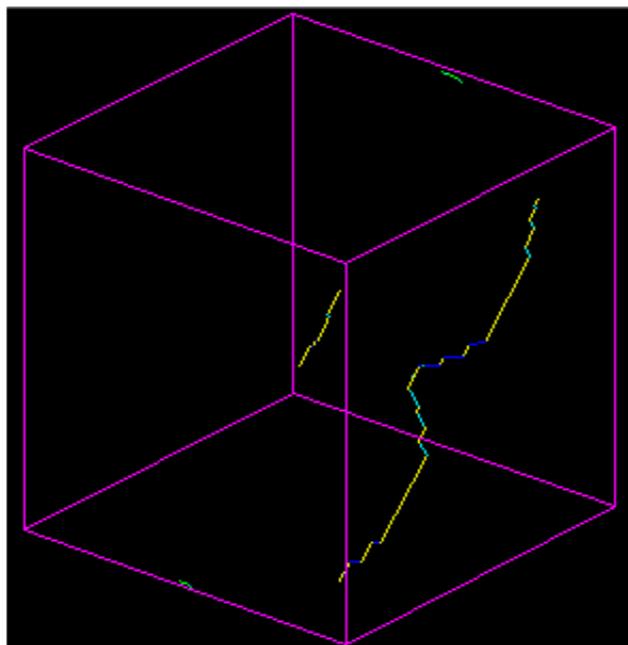
Courtesy of Markus Buehler. Used with permission.

**Schematic of a Dislocation
Pile up at a Grain Boundary**

Origin of dislocation

The number of dislocations in a material is expressed as the **dislocation density** - the total dislocation length per unit volume or the number of dislocations intersecting a unit area. Dislocation densities can vary from 10^5 cm^{-2} in carefully grown metal crystals to 10^{12} cm^{-2} in heavily deformed metals.

Most crystalline materials, especially metals, have dislocations in their as-formed state, mainly as a result of stresses (mechanical, thermal...) associated with the forming process.

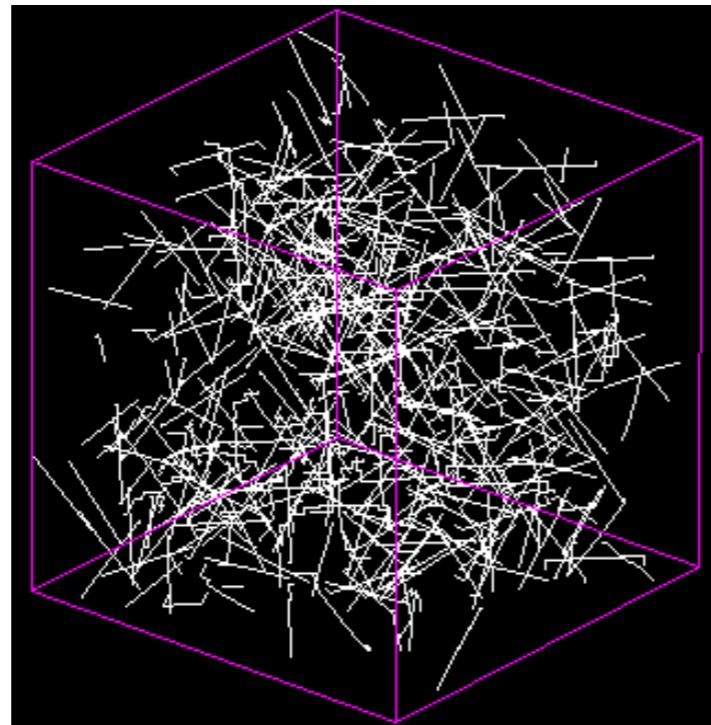


Computer simulation of Frank-Read source: Emission of dislocation loops from a dislocation segment pinned at its ends

<http://zig.onera.fr/lem/DisGallery/3D.html>

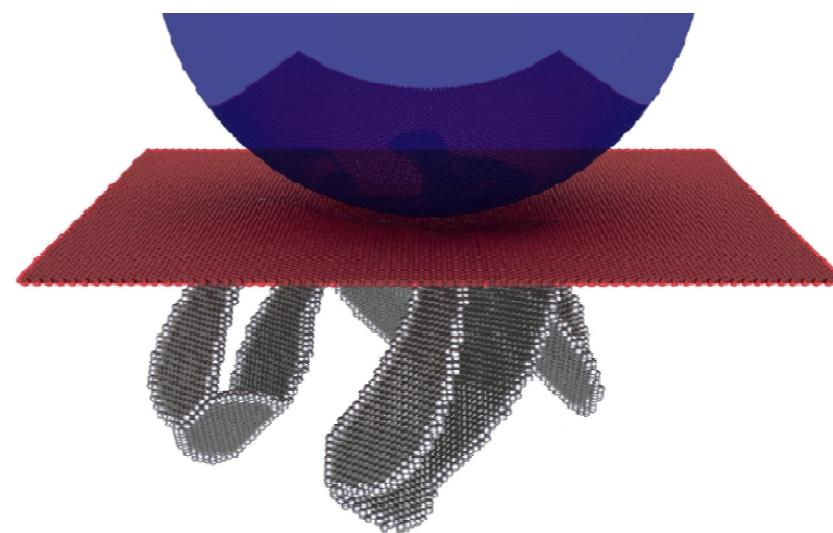
Sources of dislocations

The number of dislocations increases dramatically during plastic deformation. Dislocations spawn from existing dislocations, grain boundaries and surfaces.



Simulation of plastic deformation in a fcc single crystal (Cu) of linear dimension 15 micrometers.

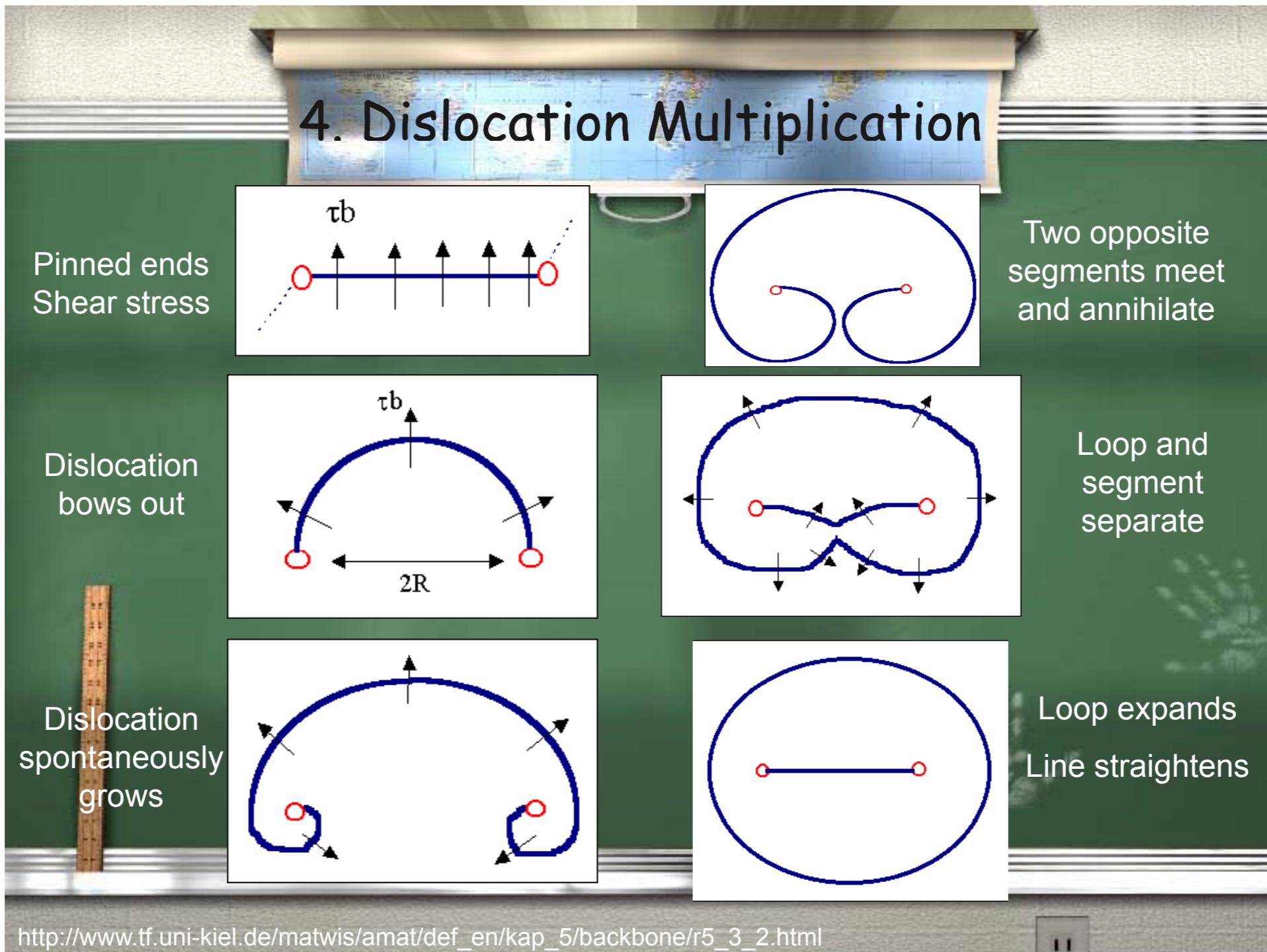
<http://zig.onera.fr/lem/DisGallery/3D.html>



Emission of dislocation loops in nanoindentation of copper

<http://merapi.physik.uni-kl.de/~gerolf/Nanoindentation/>

Dislocation multiplications



Courtesy of Helmut Föll. Used with permission.

Frank-Reed sources

Frank-Read Source

- Dislocation is pinned at both ends
- Shear stress is exerted on slip plane
- Force causes dislocation to lengthen and bend
- Dislocation spontaneously grows when
 - Shear stress overcomes restoring force
 - Past the semicircular equilibrium state
- Generate many dislocations on slip planes

Image removed due to copyright restrictions.
Please see http://commons.wikimedia.org/wiki/File:Frank-Read_Source.png

The diagram shows a series of five rectangular blocks representing a crystal lattice. A red line labeled 'Slip Plane' runs horizontally through the center of each block. In the first block, a red 'L' shaped symbol is labeled 'Non-Basal Dislocation'. As the sequence progresses, the dislocation is shown bending and growing, eventually forming a complete loop that spans multiple blocks. The points A, B, C, and D are marked along the initial segment of the dislocation line in the first block.

Figure by MIT OpenCourseWare.

<http://web.earthsci.unimelb.edu.au/wilson/ice1/generations.html>
http://en.wikipedia.org/wiki/Frank-Read_Source

Twinning



Characteristics of Twinning

- Distributed over entire volume and not confined to a single plane
- Happens very quickly (speed of sound in material)
- Cooperative motion of many planes of atoms with each plane moving only a small distance
- Lattice is rotated not distorted » NOT a phase transformation

Twinning



Rules for Twinning

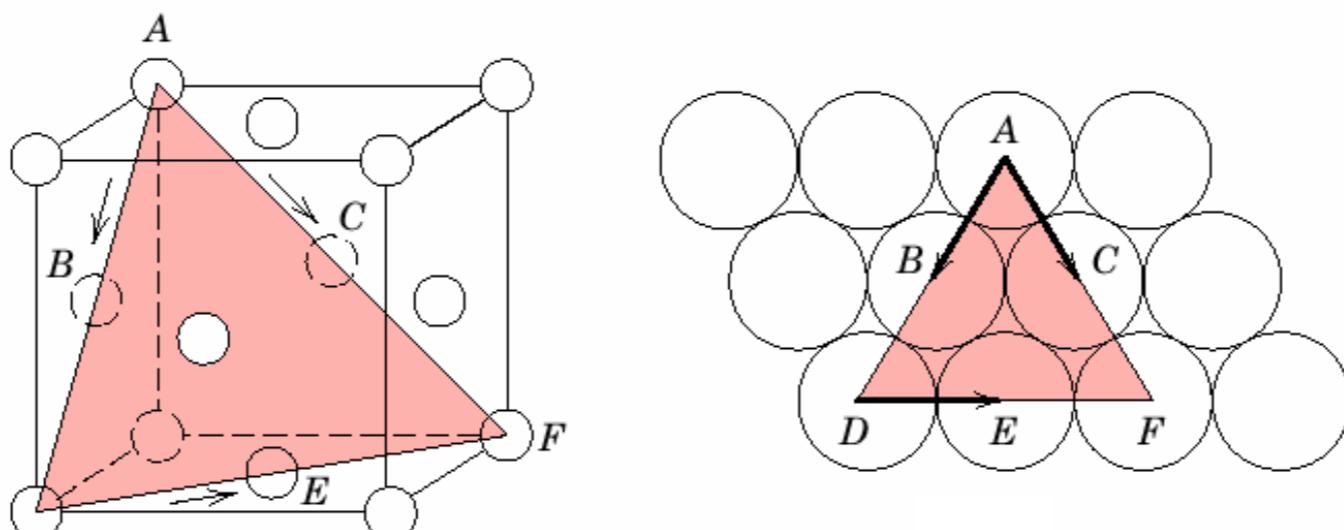
- Fundamental Rule: crystal orientation is rotated but crystal is not distorted -Crystal structure is unchanged as a result of twinning
 - Basis vectors maintain same mutual angles and length
 - Solving for the vector combinations that follow the above rules yields the twinning system

Slip systems

In single crystals there are preferred planes where dislocations move (**slip planes**). Within the slip planes there are preferred crystallographic directions for dislocation movement (**slip directions**). The set of slip planes and directions constitute **slip systems**.

The slip planes and directions are those of highest packing density. Since the distance between atoms is shorter than the average, the distance perpendicular to the plane has to be longer than average. Being relatively far apart, the planes can slip more easily relatively to each other.

BCC and FCC crystals have more slip systems as compared to HCP, there are more ways for dislocation to propagate \Rightarrow FCC and BCC crystals are more ductile than HCP crystals. Remember our discussion of close packed planes in FCC and HCP, Chapter 3.

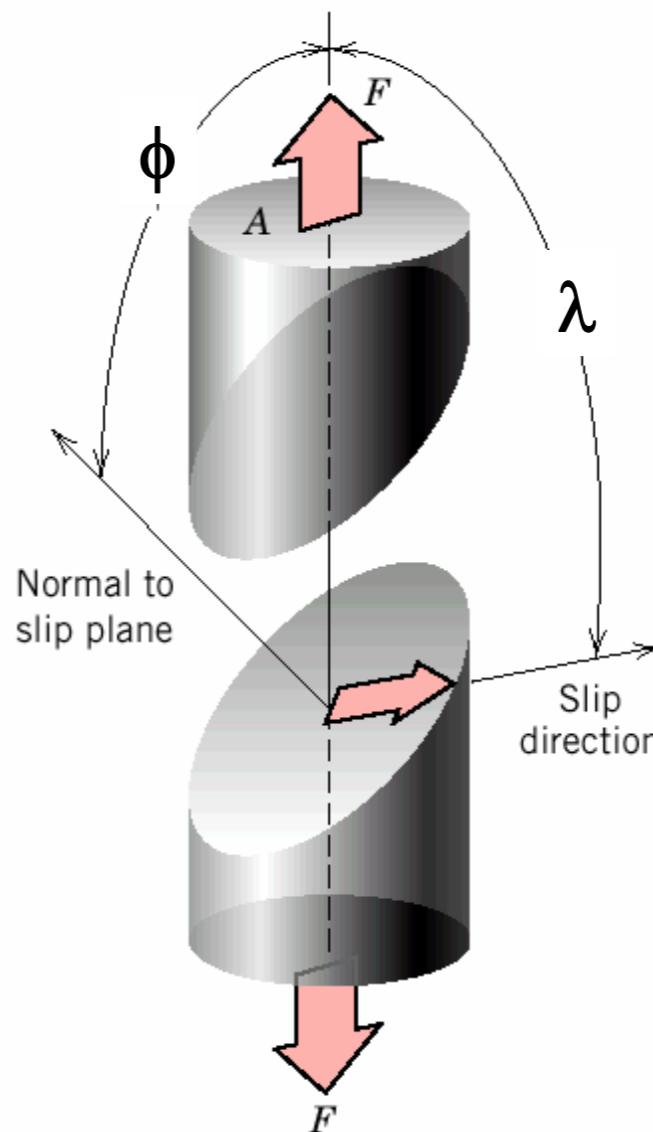


Single crystal slip deformation

Dislocations move in particular directions on particular planes (the slip system) in response to shear stresses applied along these planes and directions \Rightarrow we need to determine how the applied stress is resolved onto the slip systems.

Let us define the resolved shear stress, τ_R , (which produces plastic deformation) that result from application of a simple tensile stress, σ .

$$\tau_R = \sigma \cos \phi \cos \lambda$$



Critical resolved shear stress

When the resolved shear stress becomes sufficiently large, the crystal will start to yield (dislocations start to move along the most favorably oriented slip system). The onset of yielding corresponds to the yield stress, σ_y (Chapter 6). The minimum shear stress required to initiate slip is termed **the critical resolved shear stress**:

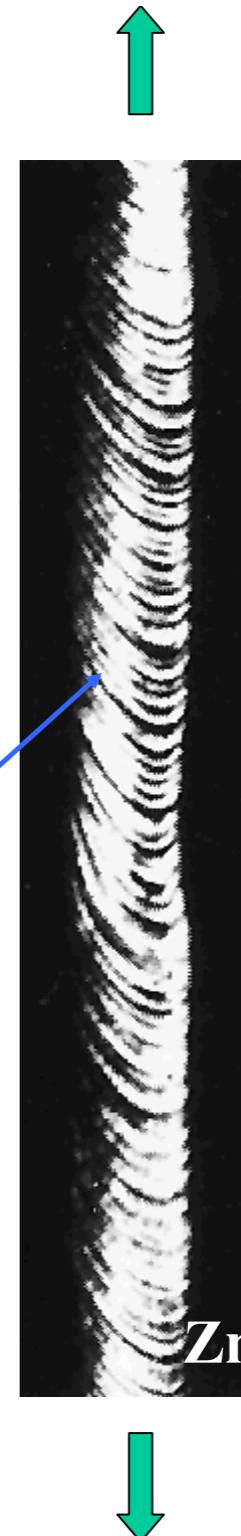
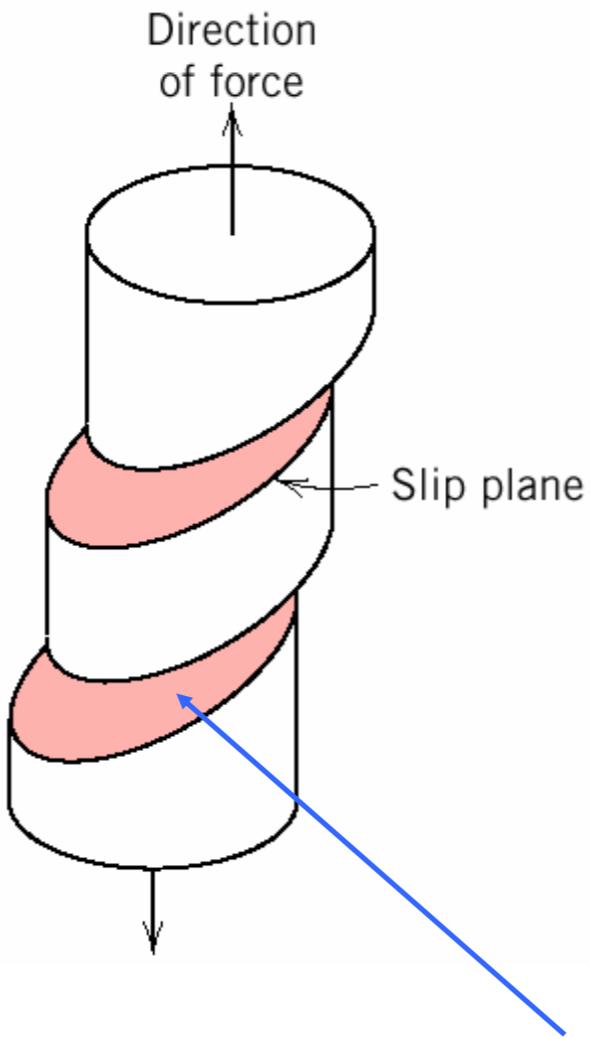
$$\tau_{\text{CRSS}} = \sigma_y (\cos \phi \cos \lambda)_{\text{MAX}}$$

$$\sigma_y = \frac{\tau_{\text{CRSS}}}{(\cos \phi \cos \lambda)_{\text{MAX}}}$$

Maximum value of $(\cos \phi \cos \lambda)$ corresponds to
 $\phi = \lambda = 45^\circ \Rightarrow \cos \phi \cos \lambda = 0.5 \Rightarrow \sigma_y = 2\tau_{\text{CRSS}}$

Slip will occur first in slip systems oriented close to these angles ($\phi = \lambda = 45^\circ$) with respect to the applied stress

Slip in a single crystal

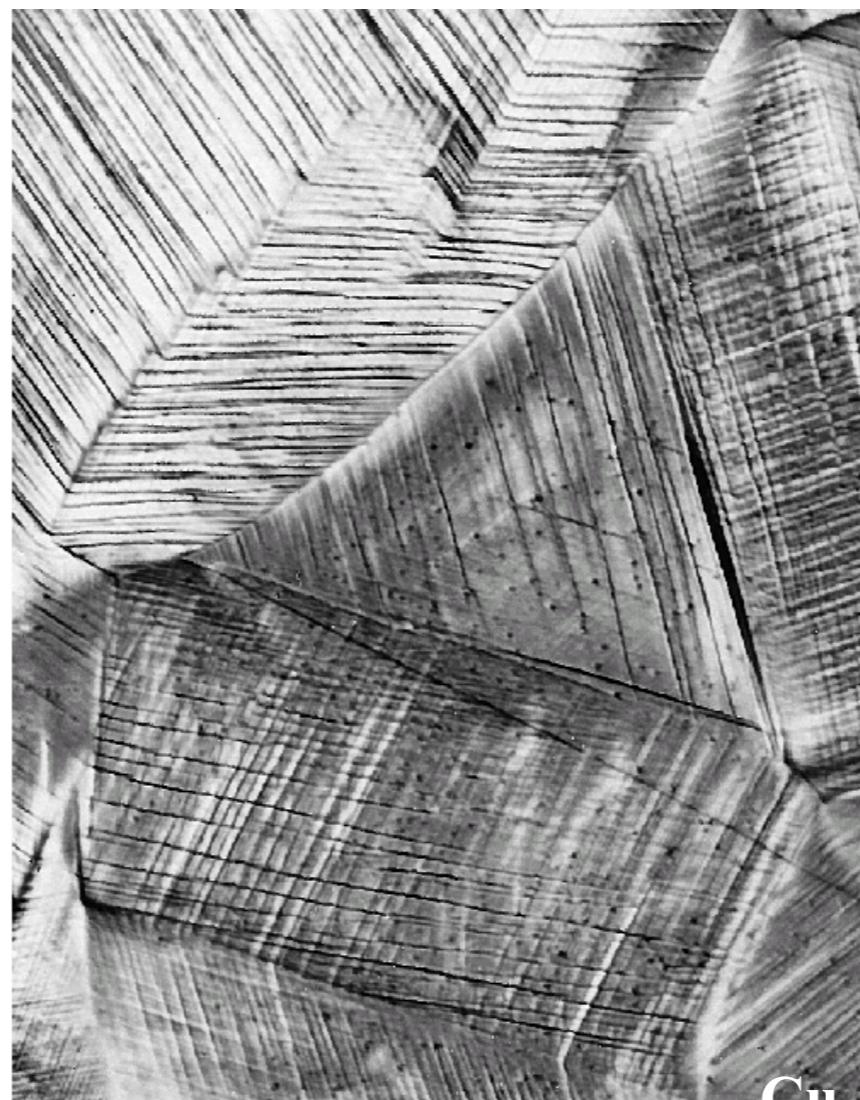


Each step (shear band) result from the generation of a large number of dislocations and their propagation in the slip system with maximum resolved shear stress.

Plastic deformation in polycrystalline materials

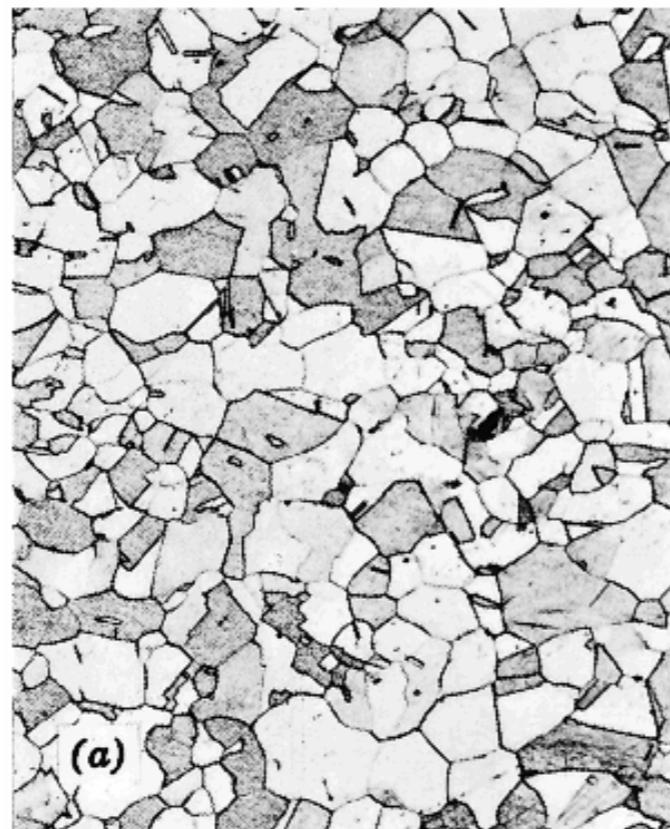
Grain orientations with respect to applied stress are random.

The dislocation motion occurs along the slip systems with favorable orientation (i.e. that with highest resolved shear stress).



Plastic deformation in polycrystalline materials

Larger plastic deformation corresponds to elongation of grains along direction of applied stress.



Before



After

Plastic deformation in polycrystalline materials

- Slip directions vary from crystal to crystal \Rightarrow Some grains are unfavorably oriented with respect to the applied stress (i.e. $\cos\phi \cos\lambda$ low)
- Even those grains for which $\cos\phi \cos\lambda$ is high may be limited in deformation by adjacent grains which cannot deform so easily
- Dislocations cannot easily cross grain boundaries because of changes in direction of slip plane and atomic disorder at grain boundaries
- **As a result, polycrystalline metals are stronger than single crystals** (the exception is the perfect single crystal without any defects, as in whiskers)

Strengthening

The ability of a metal to deform depends on the ability of dislocations to move

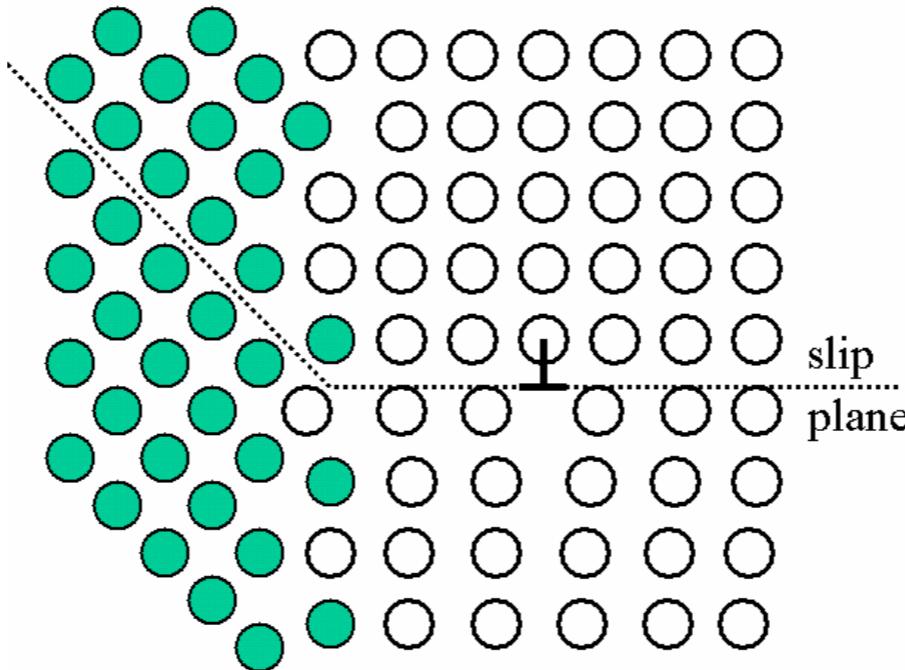
Restricting dislocation motion makes the material stronger

Mechanisms of strengthening in single-phase metals:

- grain-size reduction
- solid-solution alloying
- strain hardening
- Precipitation hardening

Ordinarily, strengthening reduces ductility

Strengthening by grain-size reduction



Grain boundary barrier to dislocation motion: slip plane discontinues or change orientation.

Small angle grain boundaries are not very effective in blocking dislocations.

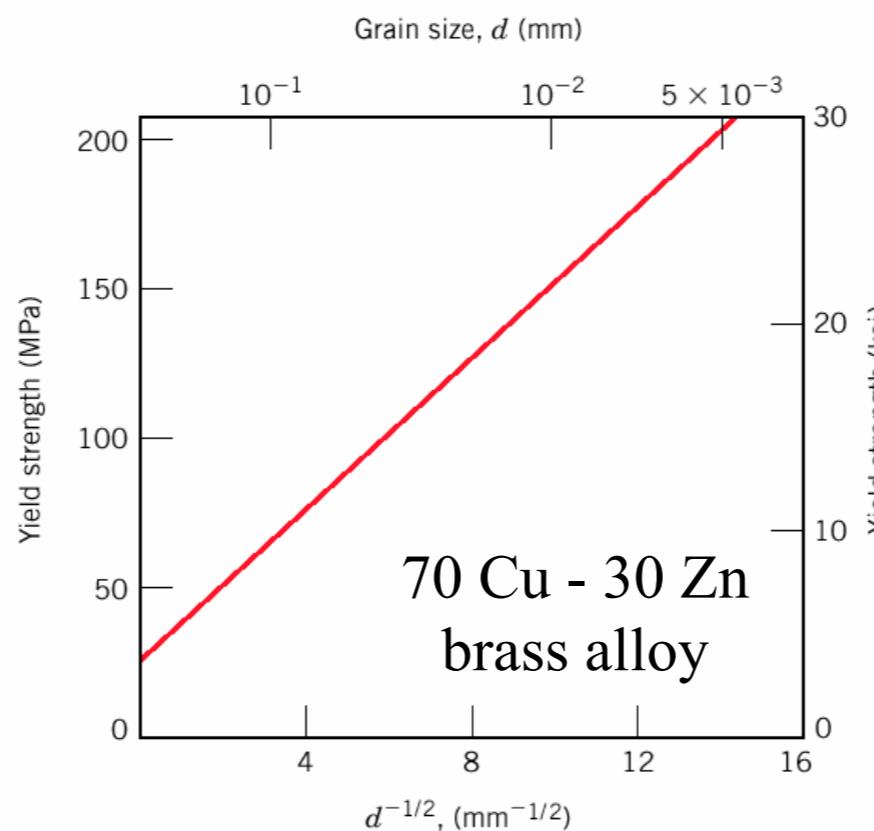
High-angle grain boundaries block slip and increase strength of the material. A stress concentration at end of a slip plane may trigger new dislocations in an adjacent grain.

Strengthening by grain-size reduction II

The finer the grains, the larger the area of grain boundaries that impedes dislocation motion. Grain-size reduction usually improves toughness as well. Usually, the yield strength varies with grain size d according to [Hall-Petch equation](#):

$$\sigma_y = \sigma_0 + k_y / \sqrt{d}$$

where σ_0 and k_y are constants for a particular material, d is the average grain diameter.



Grain size d can be controlled by the rate of solidification, by plastic deformation and by appropriate heat treatment.

Solid solution strengthening-I

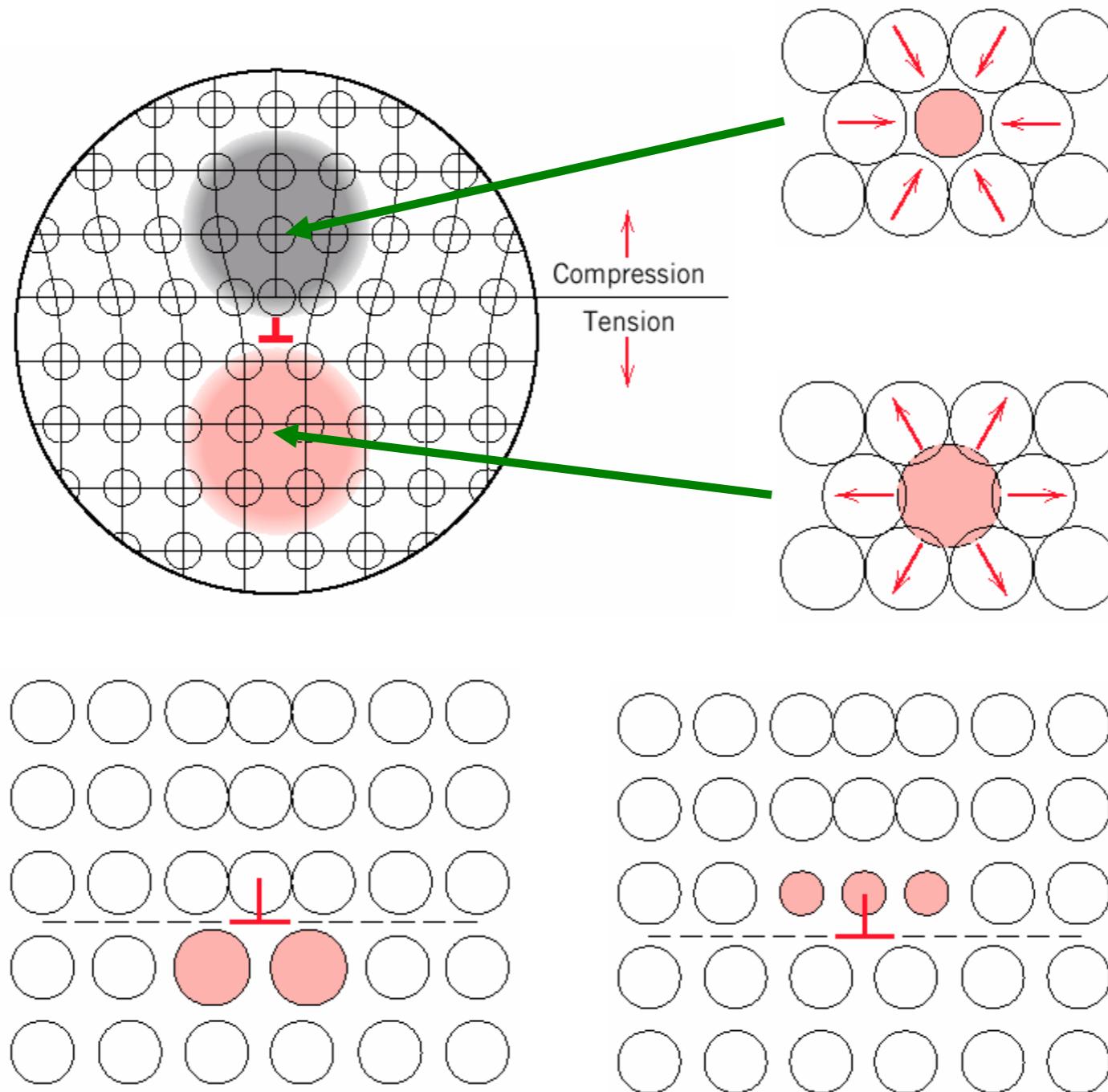
Alloys are usually stronger than pure metals

Interstitial or substitutional impurities cause lattice strain. As a result, these impurities interact with dislocation strain fields and **hinder dislocation motion.**

Impurities tend to diffuse and **segregate around dislocation cores** to find atomic sites that suit their radii. This reduces the overall strain energy and “anchors” the dislocations.

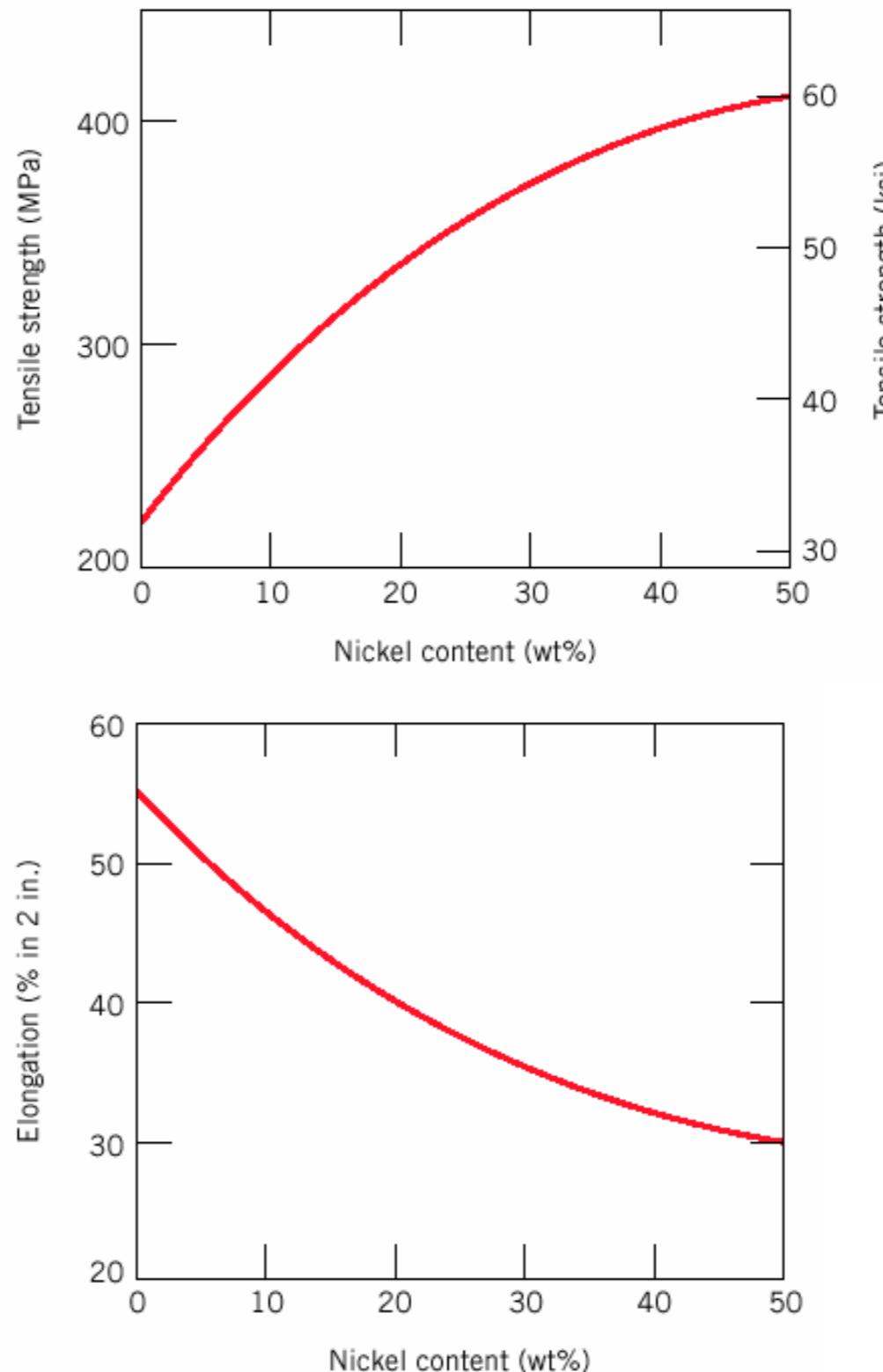
Motion of a dislocation core away from the impurities moves it to a region of lattice where the atomic strains are greater (i.e. the dislocation strains are no longer compensated by the impurity atoms).

Solid solution strengthening-II



Smaller and larger substitutional impurities tend to diffuse into strained regions around dislocations, leading to partial cancellation of impurity-dislocation lattice strains.

Solid solution strengthening-III



Strengthening by increase of dislocation density (Strain Hardening = Work Hardening = Cold Working)

Ductile metals become stronger when they are deformed plastically at temperatures well below the melting point.

The reason for strain hardening is the increase of dislocation density with plastic deformation. The average distance between dislocations decreases and dislocations start blocking the motion of each other.

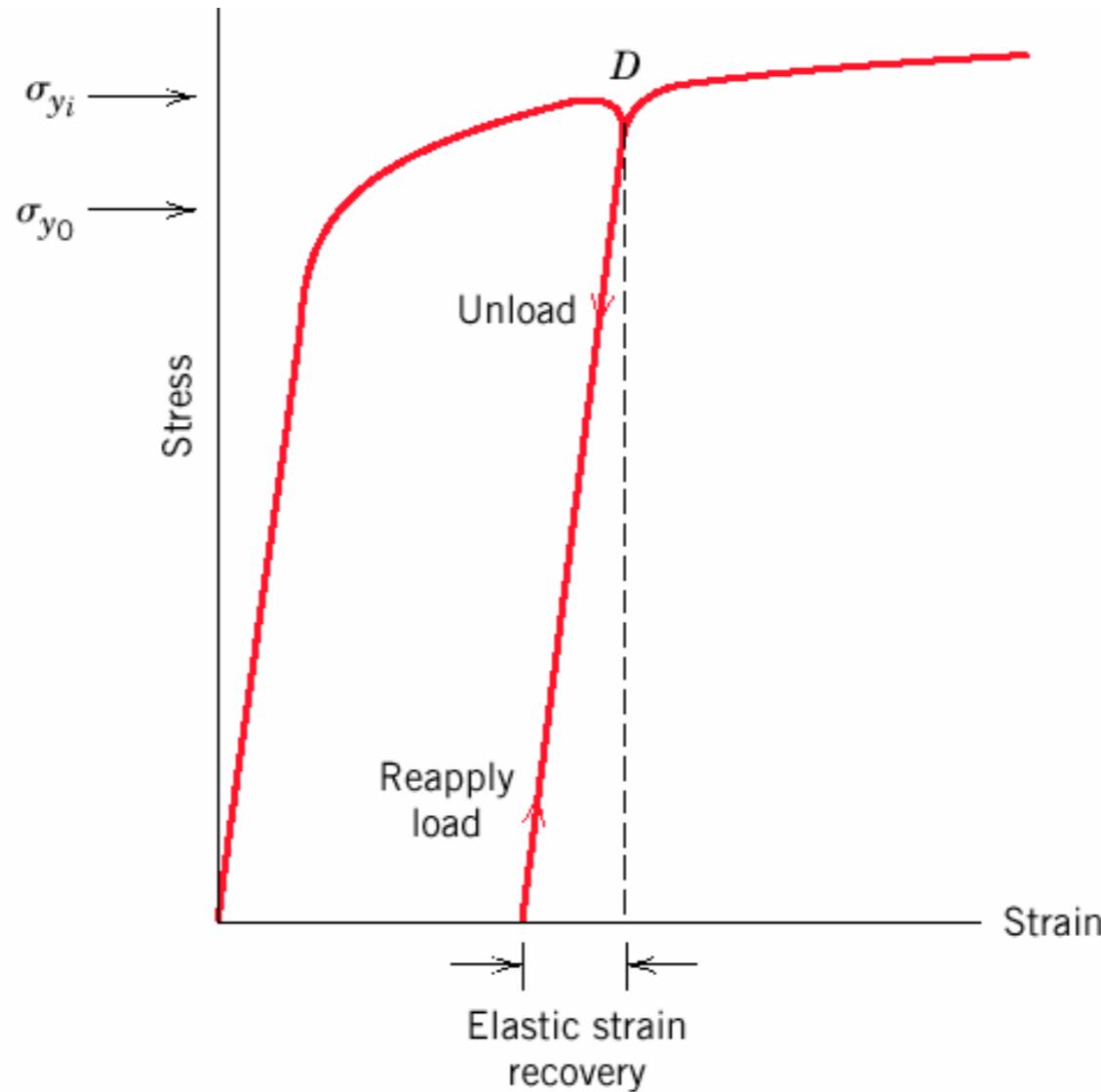
The percent cold work (%CW) is often used to express the degree of plastic deformation:

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

where A_0 is the original cross-section area, A_d is the area after deformation.

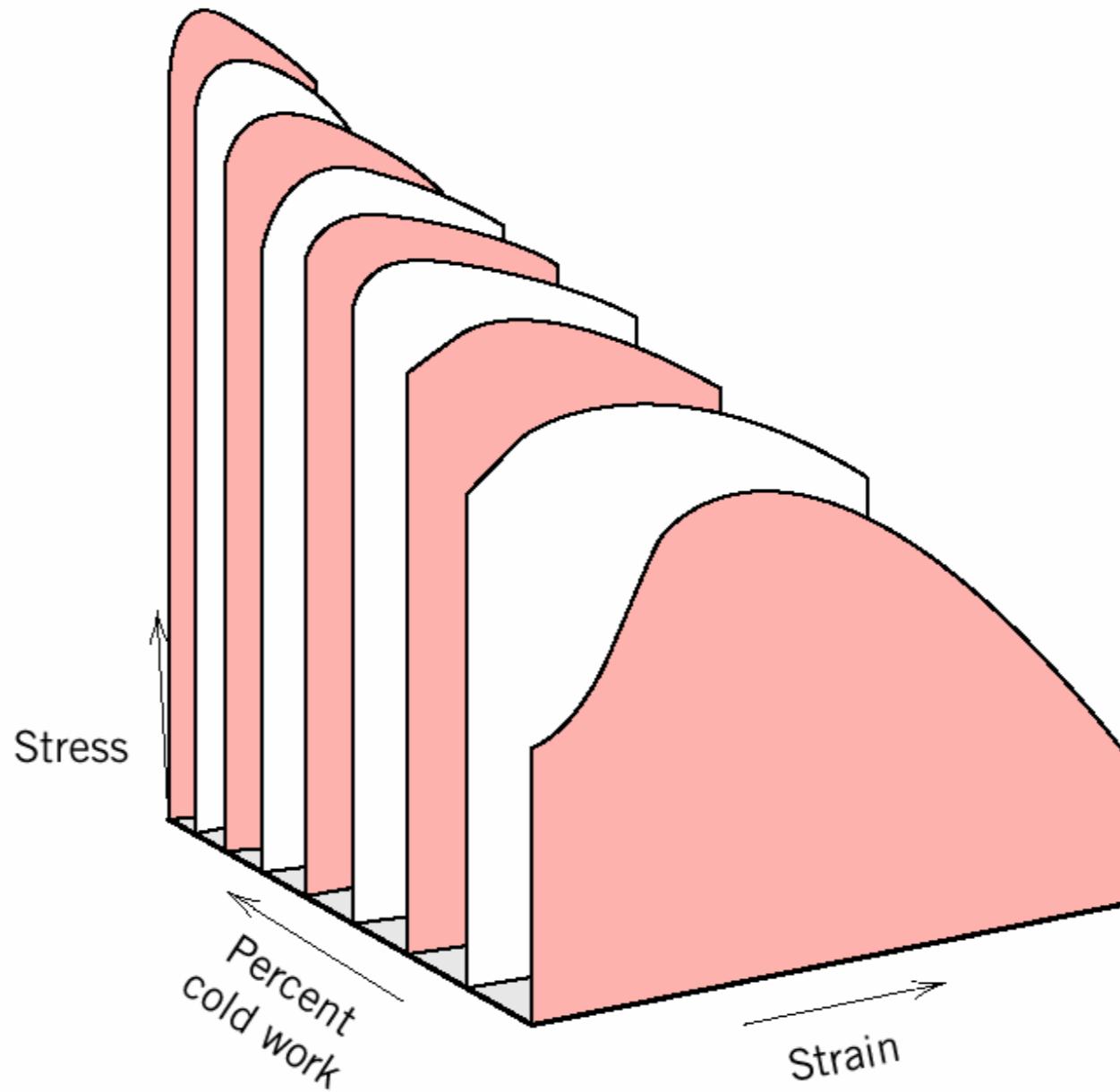
%CW is just another measure of the degree of plastic deformation, in addition to strain.

Strain hardening



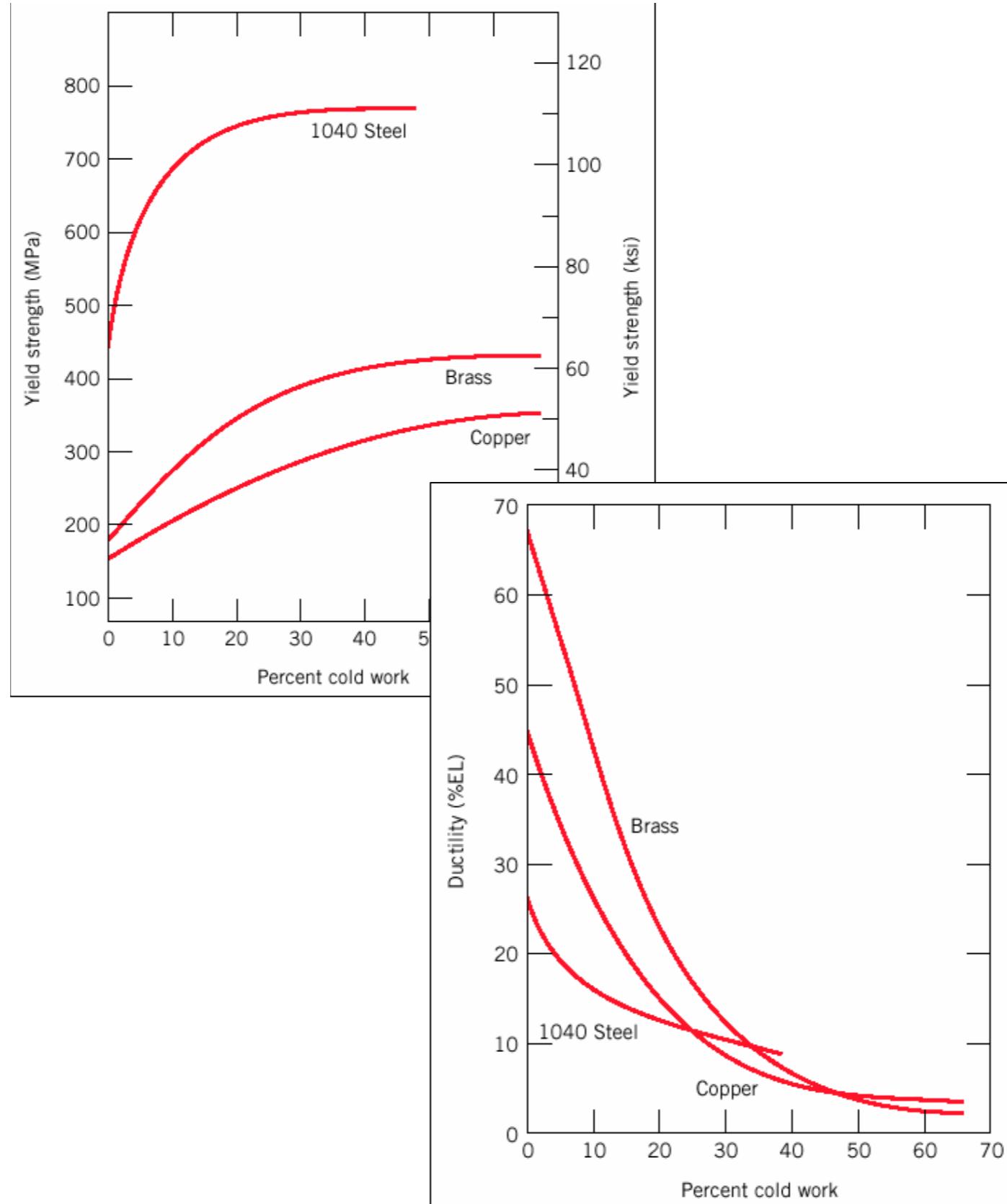
New yield strength σ_{y_i} is higher than the initial yield strength, σ_{y_0} . The reason for this effect - strain hardening.

Strain hardening-III



Yield strength and hardness are increasing as a result of strain hardening but **ductility is decreasing** (material becomes more brittle).

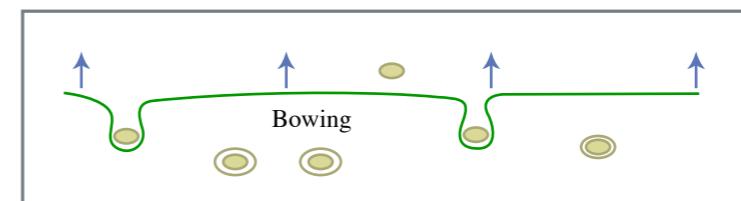
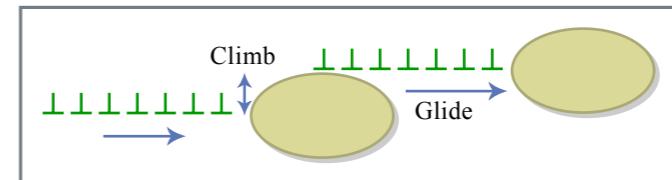
Strain hardening-IV



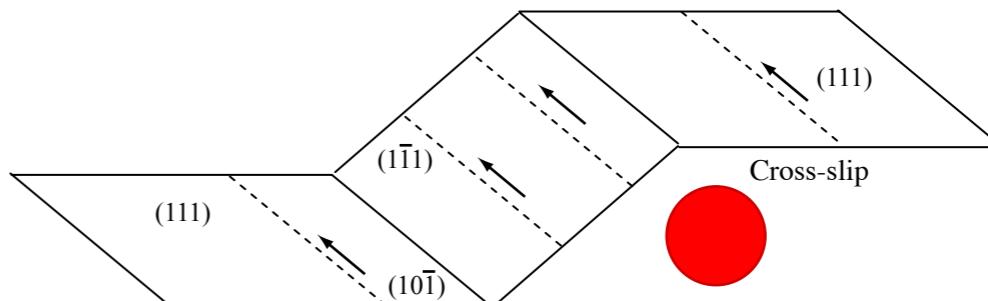
Precipitation hardening

OROWAN LOOPING

- Precipitates act as pinning points for dislocations
- Bowing leads to unpinning leaving behind dislocation loops around the particles



Figures by MIT OpenCourseWare.



Courtesy of Krystyn Van Vliet. Used with permission.

Please also see "Strengthening Processes: Dispersion Hardening."
aluMATTER, University of Liverpool.

Dislocation bypass around precipitates

http://www.cemes.fr/r2_rech/r2_sr3_mc2/videos

<http://aluminium.matter.org.uk/>

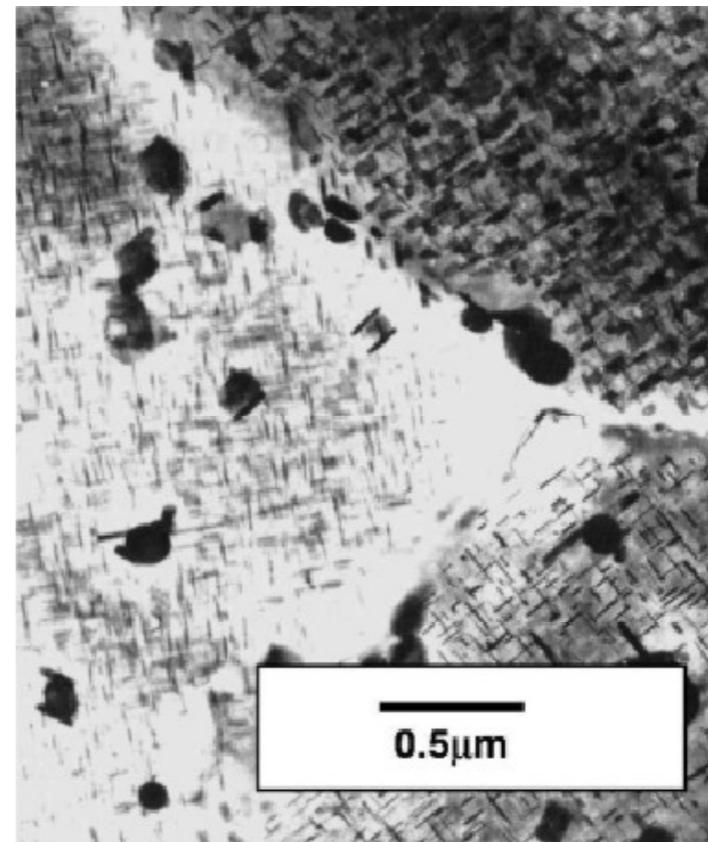
Precipitation hardening

OROWAN LOOPING

- Yield Stress to overcome obstacles:

$$\tau_y \approx \frac{\mu b}{L} = \alpha \mu b \sqrt{\rho_{\perp}}$$

- Dislocation density has units of 1/Area
- Ageing Treatment
 - Precipitation Hardening
 - eg. Al – Cu alloys
 - “Overageing”



Microstructure of an aged Al – 4 % Cu alloy showing CuAl₂ precipitates

<http://aluminium.matter.org.uk/>

Fig. 1204.03.18 in Jacobs, M. H. "1204 Precipitation Hardening."
Introduction to Aluminium Metallurgy. TALAT, 1999.

Precipitation hardening

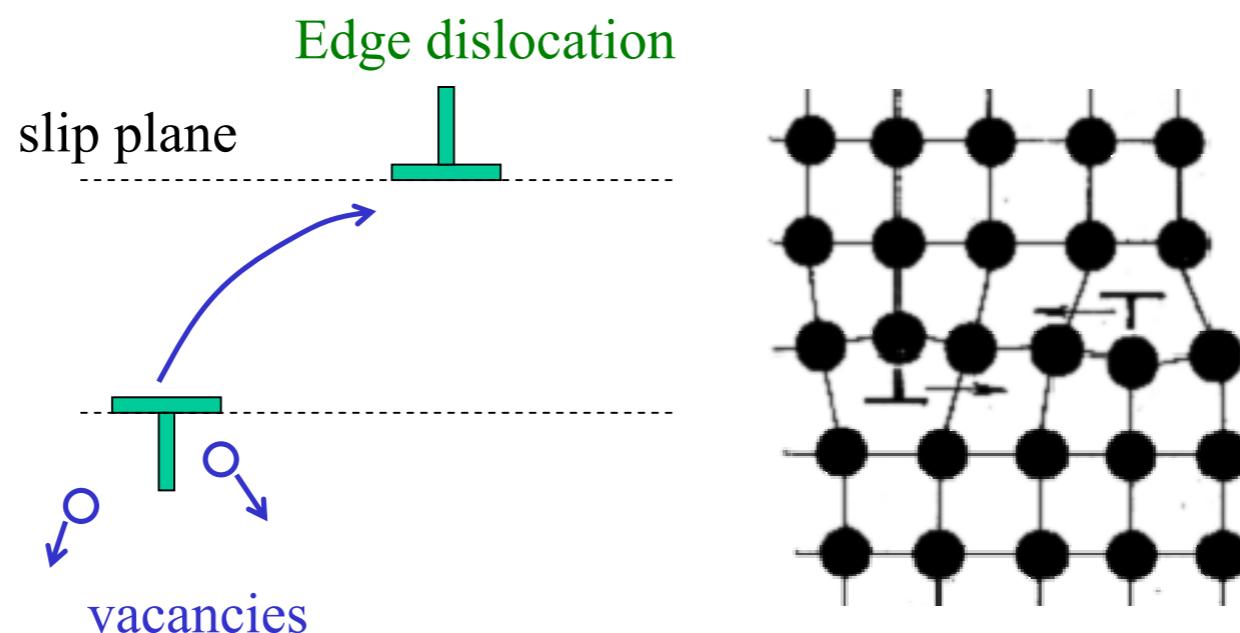
Recovery, recrystallization and grain growth

- Plastic deformation increases dislocation density (single and polycrystalline materials) and changes grain size distributions (polycrystalline materials).
- This corresponds to stored strain energy in the system (dislocation strain fields and grain distortions).
- When applied external stress is removed - most of the dislocations, grain distortions and associated strain energy are retained.
- Restoration to the state before cold-work can be done by heat-treatment and involves two processes: recovery and recrystallization. These may be followed by grain growth.

Recovery

Heating → increased diffusion → enhanced dislocation motion → decrease in dislocation density by annihilation, formation of low-energy dislocation configurations → relieve of the internal strain energy

Some of the mechanisms of dislocation annihilation:



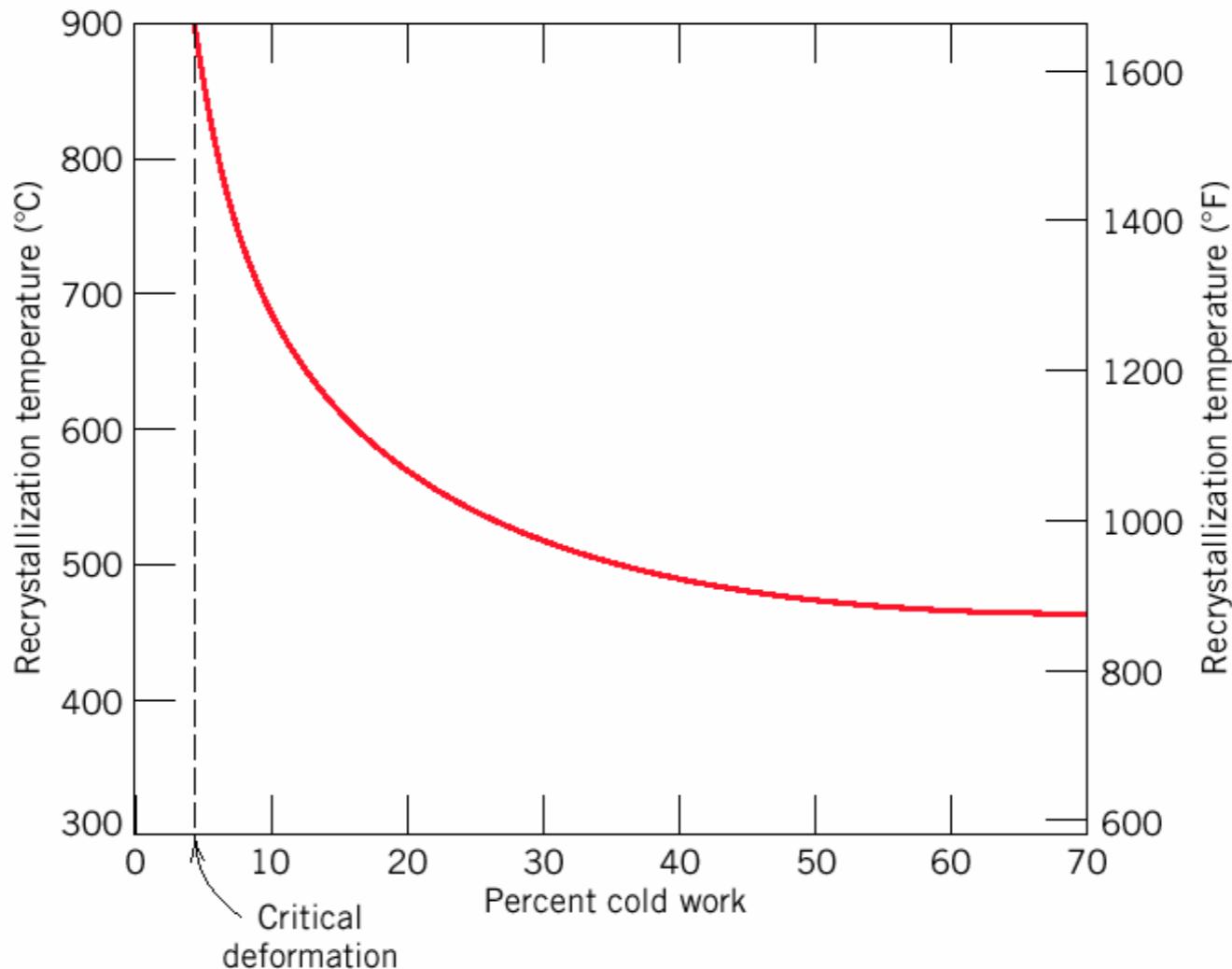
Recrystallization-I

- Even after recovery the grains can be strained. These strained grains of cold-worked metal can be replaced, upon heating, by strain-free grains with low density of dislocations.
- This occurs through **recrystallization – nucleation and growth of new grains.**
- The *driving force* for recrystallization is the difference in internal energy between strained and unstrained material.
- Grain growth involves short-range diffusion → the extent of recrystallization depends on both temperature and time.
- Recrystallization is slower in alloys as compared to pure metals

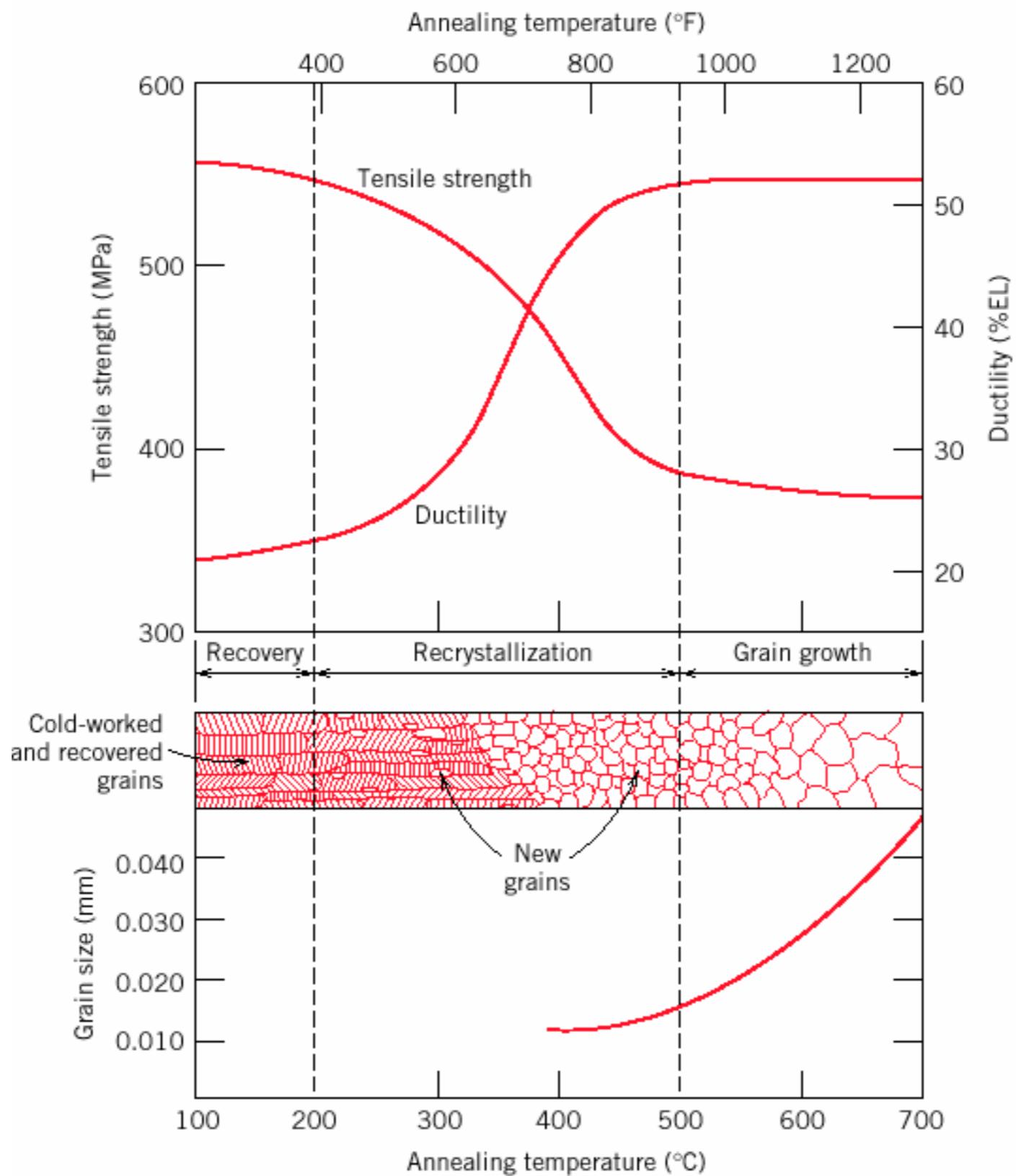
Recrystallization-II

Recrystallization temperature: The temperature at which the process is complete in one hour. It is typically 1/3 to 1/2 of the melting temperature (can be as high as 0.7 T_m in some alloys).

Recrystallization temperature increases as the %CW is decreased. Below a "critical deformation", recrystallization does not occur.

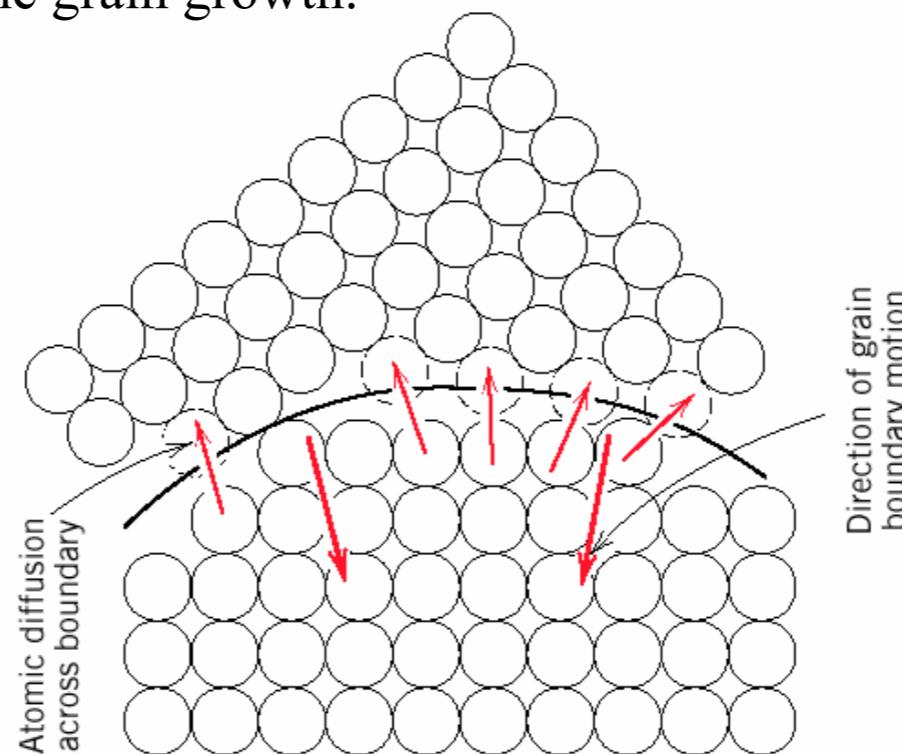


Recrystallization-III



Grain growth

- If deformed polycrystalline material is maintained at annealing temperature following complete recrystallization, then further **grain growth** occurs.
- *Driving force* is reduction of the total grain boundary area and, hence, the energy of the system. Big grains grow at the expense of the small ones.
- Grain growth during annealing occurs in all polycrystalline materials (i.e. they do not have to be deformed or undergo recrystallization first).
- Boundary motion occurs by short range diffusion of atoms across the grain boundary → strong temperature dependence of the grain growth.



Summary

Make sure you understand language and concepts:

- Cold working
- Critical resolved shear stress
- Dislocation density
- Grain growth
- Lattice strain
- Recovery
- Recrystallization
- Recrystallization temperature
- Resolved shear stress
- Slip
- Slip system
- Strain hardening
- Solid-solution strengthening

Failure of Materials

- Mechanisms of brittle vs. ductile fracture
- Basic principles of fracture mechanics
- Fatigue (cyclic stresses)
- Crack initiation and propagation
- Creep (time dependent deformation)

Failure of Materials

How do Materials Break?

- **Ductile vs. brittle fracture**
- **Principles of fracture mechanics**
 - ✓ Stress concentration
- **Impact fracture testing**
- **Fatigue** (cyclic stresses)
 - ✓ Cyclic stresses, the S—N curve
 - ✓ Crack initiation and propagation
 - ✓ Factors that affect fatigue behavior
- **Creep** (time dependent deformation)
 - ✓ Stress and temperature effects
 - ✓ Alloys for high-temperature use

Not tested: *in 8.5 Fracture Toughness*
8.14 Data extrapolation methods

Fracture of Materials

Fracture: separation of a body into pieces due to stress, at temperatures below the melting point.

Steps in fracture:

- crack formation
- crack propagation

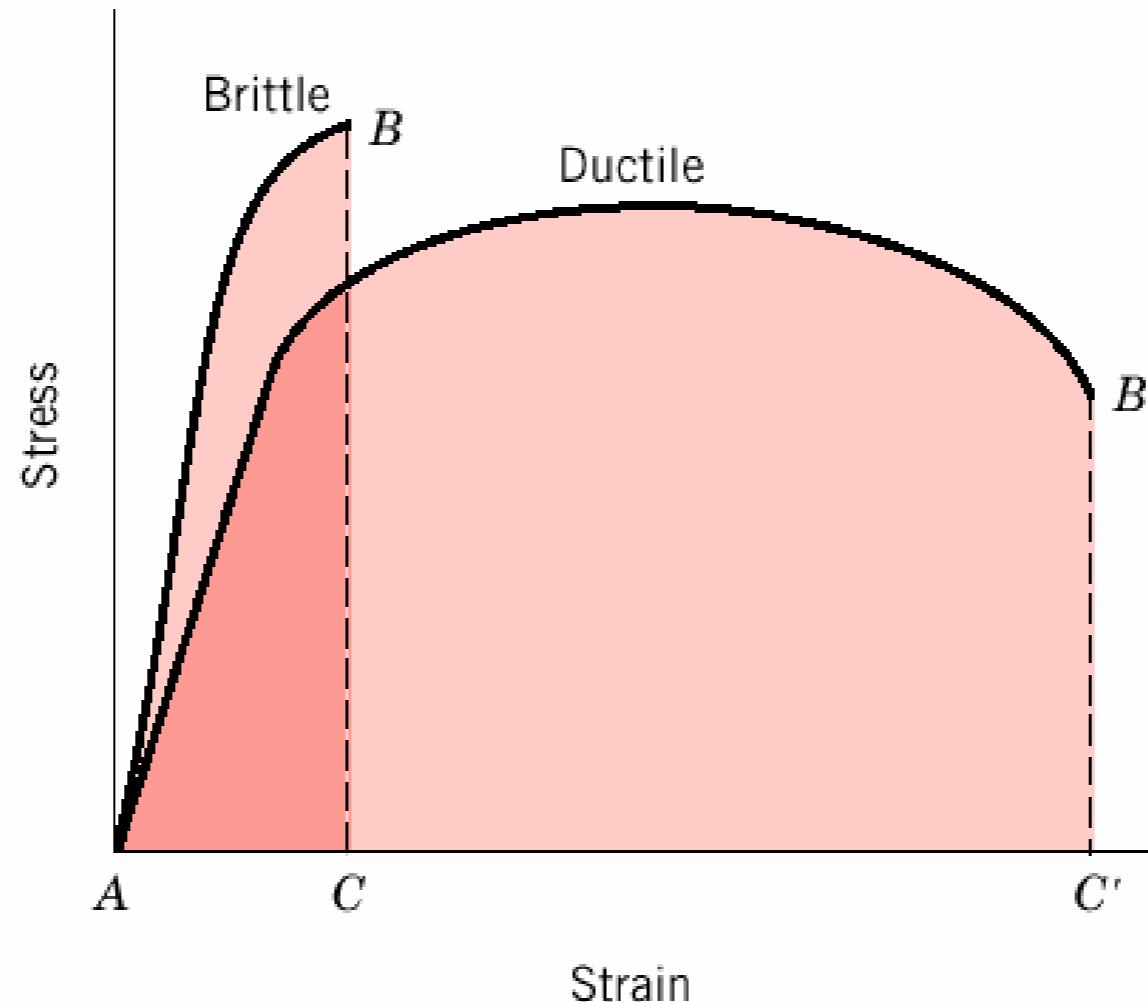
Depending on the ability of material to undergo plastic deformation before the fracture two fracture modes can be defined - **ductile or brittle**

- **Ductile fracture** - most metals (not too cold):
 - Extensive plastic deformation ahead of crack
 - Crack is “stable”: resists further extension unless applied stress is increased
- **Brittle fracture** - ceramics, ice, cold metals:
 - Relatively little plastic deformation
 - Crack is “unstable”: propagates rapidly without increase in applied stress

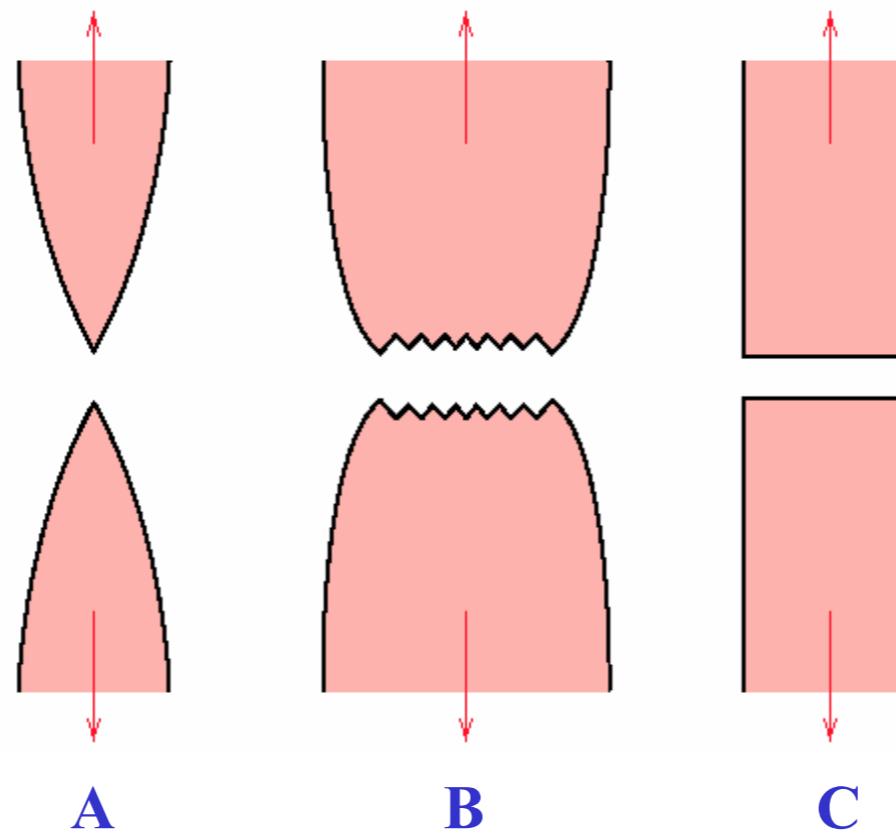
Ductile fracture is preferred in most applications

Brittle vs. ductile fracture

- **Ductile materials** - extensive plastic deformation and energy absorption (“toughness”) before fracture
- **Brittle materials** - little plastic deformation and low energy absorption before fracture

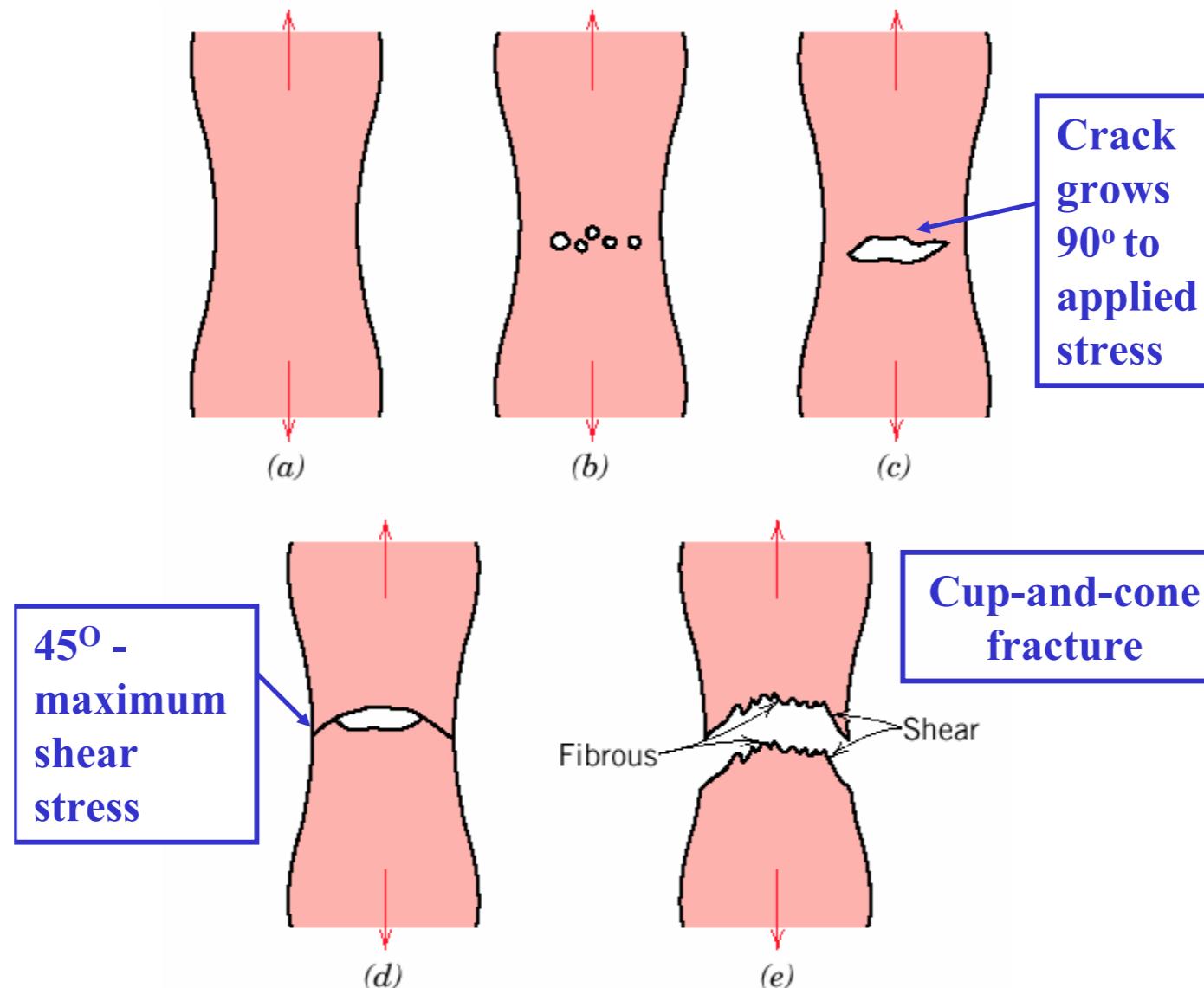


Brittle vs. ductile fracture



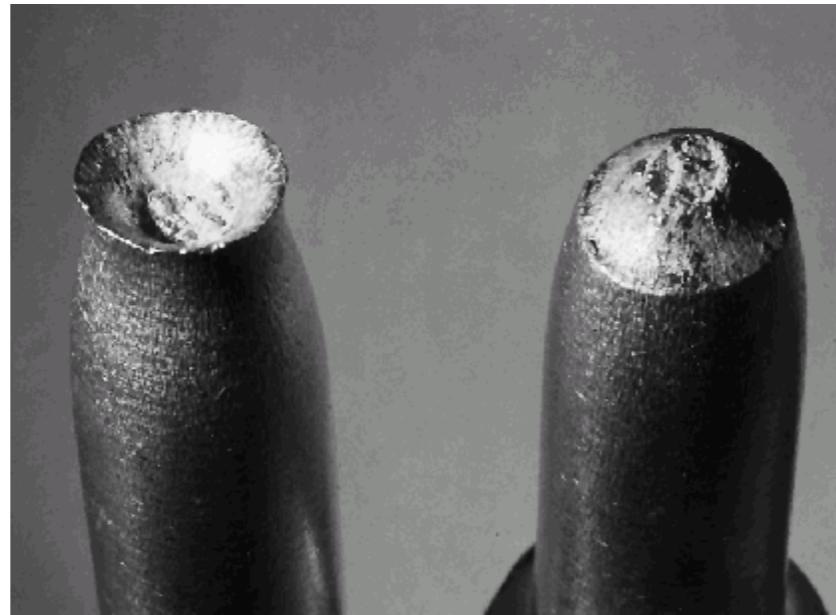
- A. Very ductile**, soft metals (e.g. Pb, Au) at room temperature, other metals, polymers, glasses at high temperature.
- B. Moderately ductile fracture**, typical for ductile metals
- C. Brittle fracture**, cold metals, ceramics.

Ductile fracture (dislocation mediated)

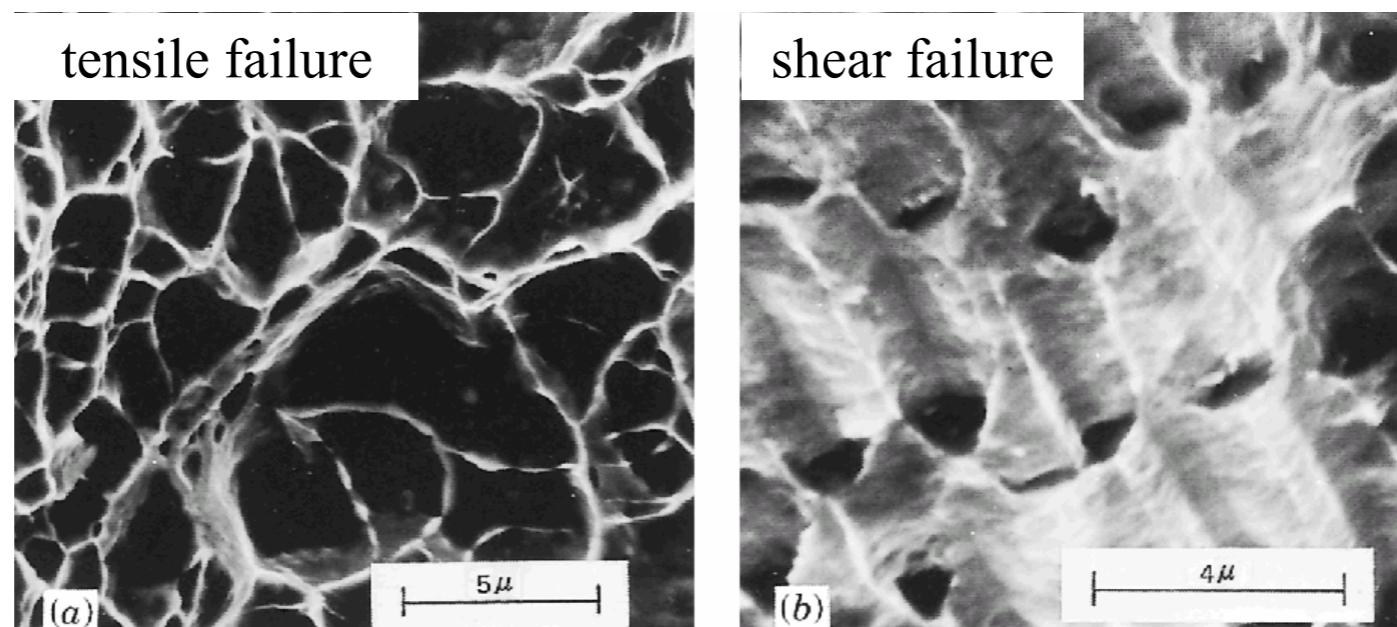


- (a) Necking
- (b) Formation of microvoids
- (c) Coalescence of microvoids to form a crack
- (d) Crack propagation by shear deformation
- (e) Fracture

Ductile fracture



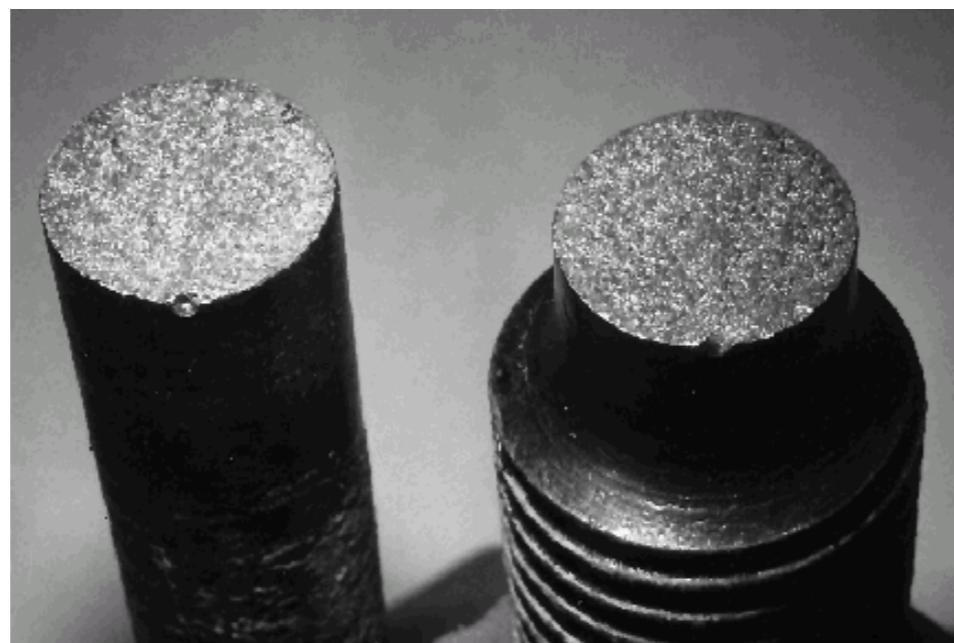
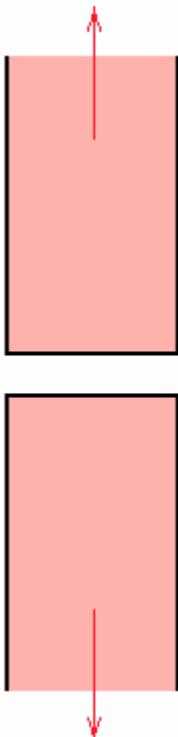
(Cup-and-cone fracture in Al)



Scanning Electron Microscopy: *Fractographic* studies at high resolution. Spherical “dimples” correspond to microvoids that initiate crack formation.

Brittle fracture

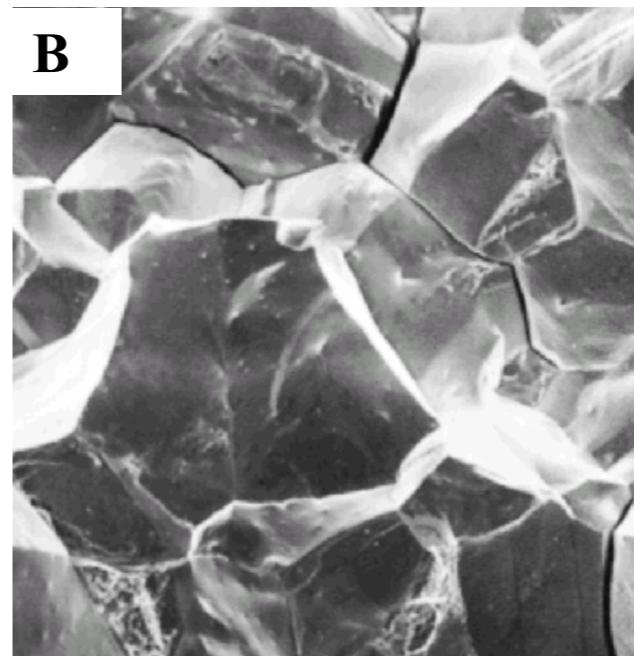
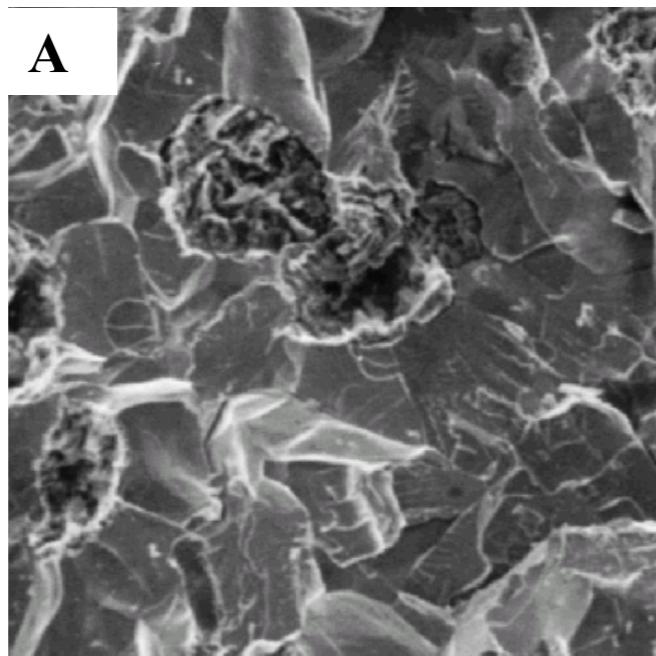
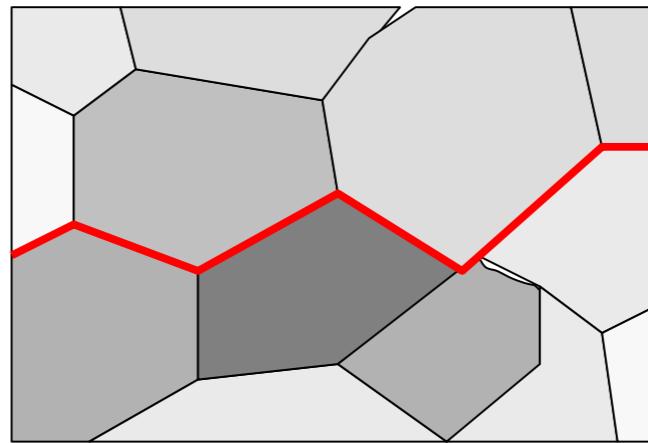
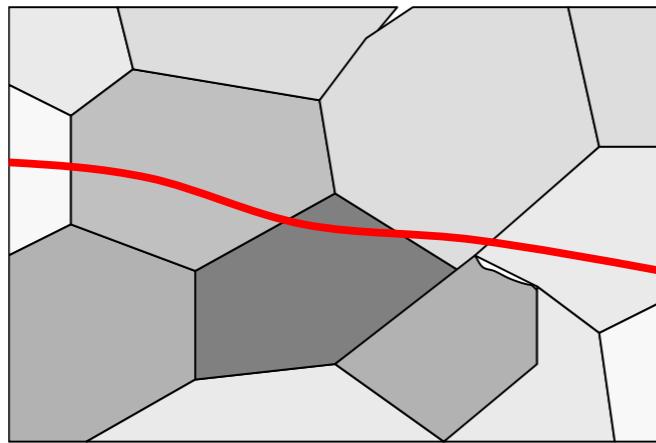
- No appreciable plastic deformation
- Crack propagation is very fast
- Crack propagates nearly perpendicular to the direction of the applied stress
- Crack often propagates by **cleavage** - breaking of atomic bonds along specific crystallographic planes (**cleavage planes**).



Brittle fracture in a mild steel

Brittle fracture

- A. Transgranular fracture:** Fracture cracks pass through grains. Fracture surface have faceted texture because of different orientation of cleavage planes in grains.
- B. Intergranular fracture:** Fracture crack propagation is along grain boundaries (grain boundaries are weakened or embrittled by impurities segregation etc.)



Stress concentration

Fracture strength of a brittle solid is related to the cohesive forces between atoms. One can estimate that the theoretical cohesive strength of a brittle material should be $\sim E/10$. But experimental fracture strength is normally $E/100 - E/10,000$.

This much lower fracture strength is explained by the effect of **stress concentration** at microscopic flaws. The applied stress is amplified at the tips of micro-cracks, voids, notches, surface scratches, corners, etc. that are called **stress raisers**. The magnitude of this amplification depends on micro-crack orientations, geometry and dimensions.

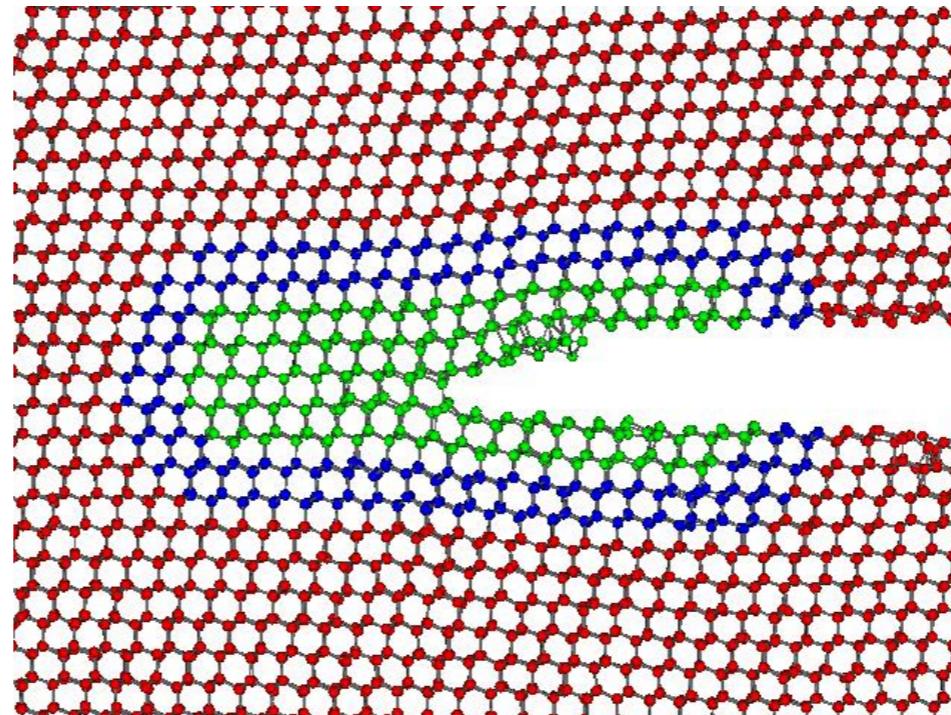
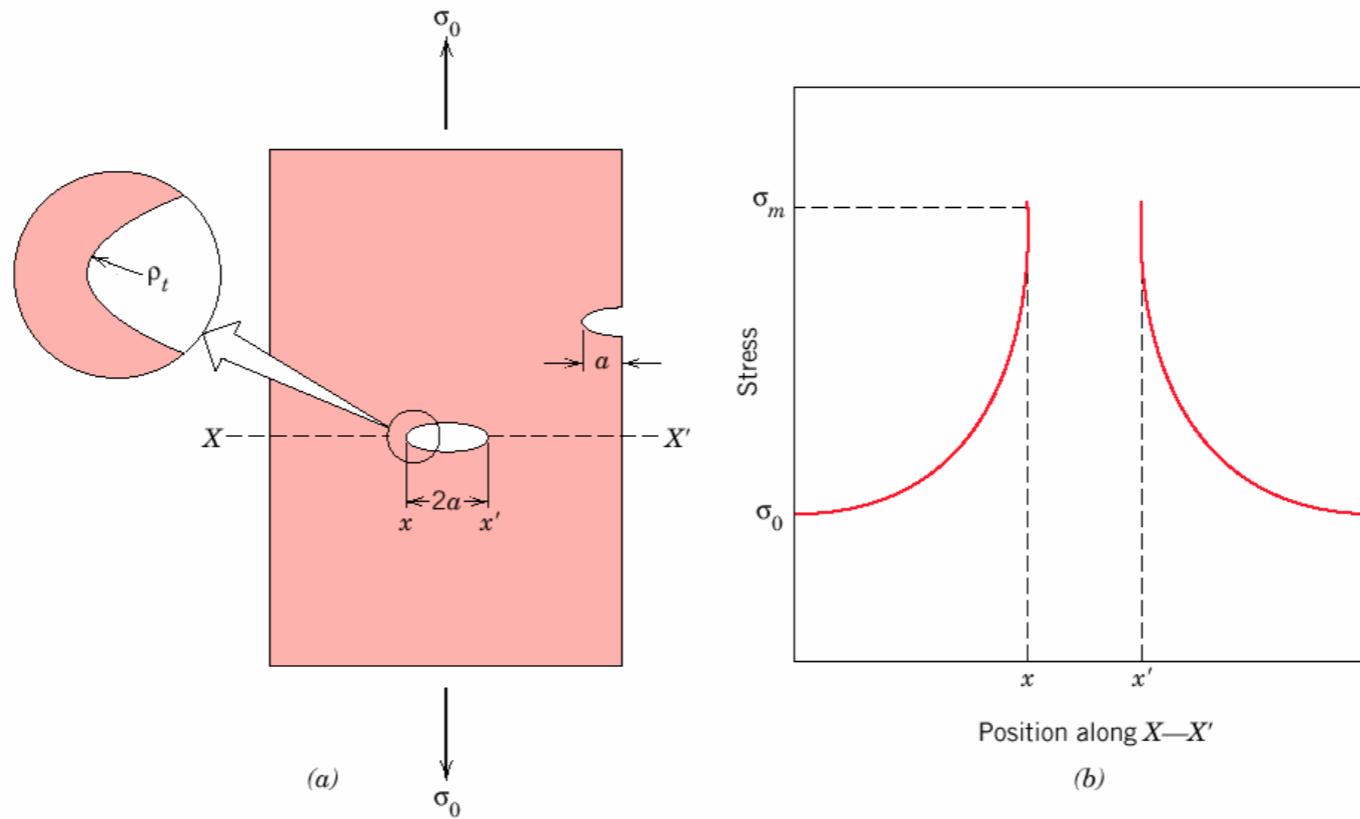


Figure by
N. Bernstein &
D. Hess, NRL

Stress concentration



For a long crack oriented perpendicular to the applied stress the maximum stress near the crack tip is:

$$\sigma_m \approx 2\sigma_0 \left(\frac{a}{\rho_t} \right)^{1/2}$$

where σ_0 is the applied external stress, a is the **half-length** of the crack, and ρ_t the radius of curvature of the crack tip. (note that a is half-length of the internal flaw, but the full length for a surface flaw).

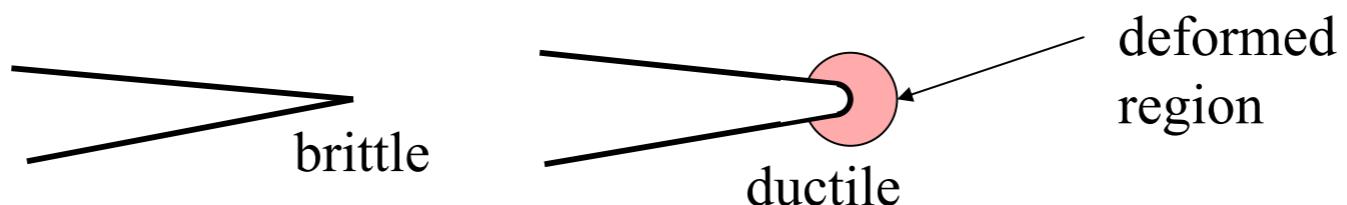
The **stress concentration factor** is: $K_t = \frac{\sigma_m}{\sigma_0} \approx 2 \left(\frac{a}{\rho_t} \right)^{1/2}$

Crack propagation

Cracks with sharp tips propagate easier than cracks having blunt tips

$$\sigma_m \approx 2\sigma_0 \left(\frac{a}{\rho_t} \right)^{1/2}$$

In ductile materials, plastic deformation at a crack tip “blunts” the crack.



Energy balance on the crack

Elastic strain energy:

- energy stored in material as it is elastically deformed
- this energy is released when the crack propagates
- creation of new surfaces requires energy

Critical stress for crack propagation: $\sigma_c = \left(\frac{2E\gamma_s}{\pi a} \right)^{1/2}$

γ_s = specific surface energy

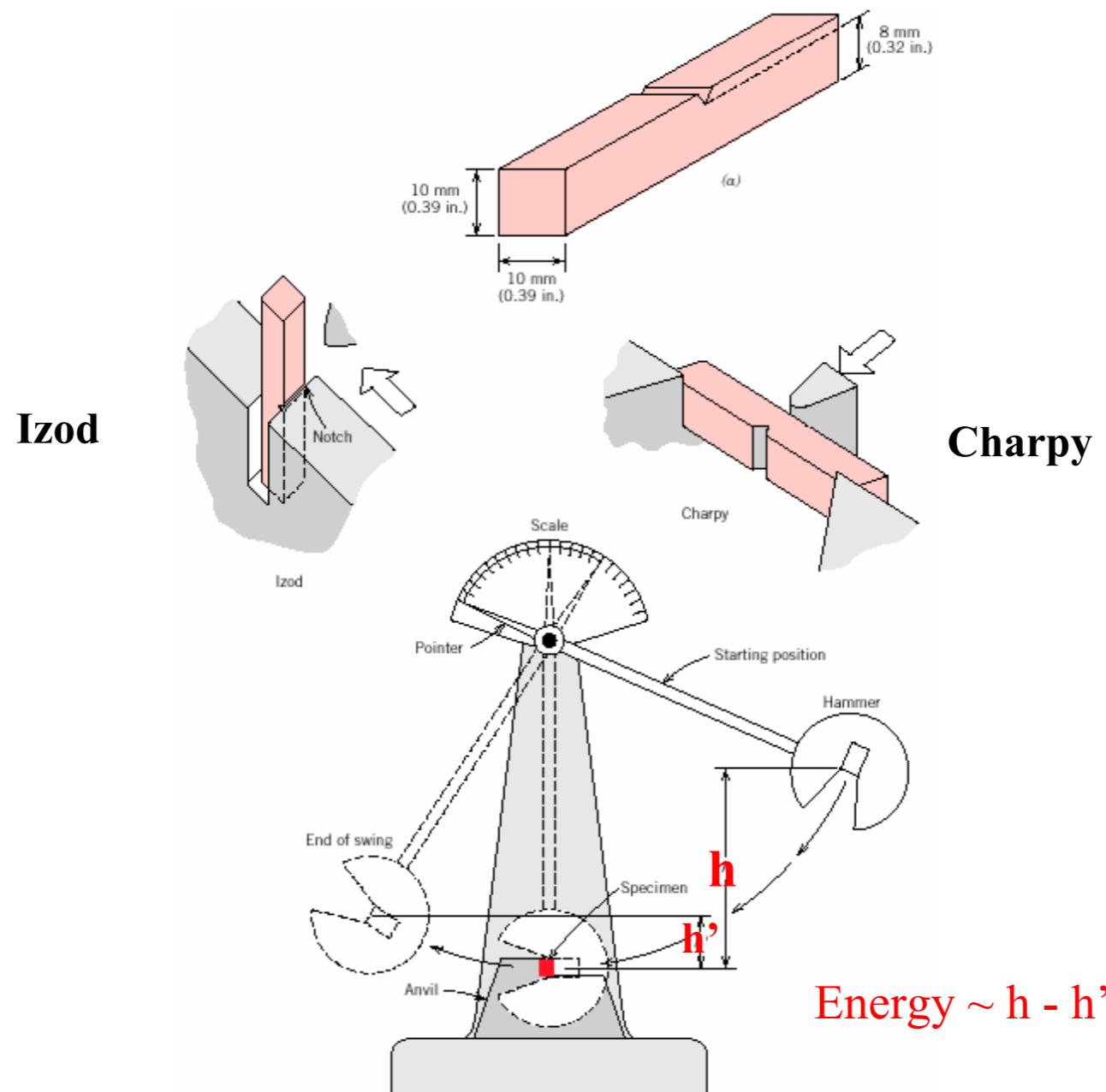
Griffith's criterion

for ductile materials γ_s should be replaced with $\gamma_s + \gamma_p$
where γ_p is plastic deformation energy

Impact fracture testing

(testing fracture characteristics under high strain rates)

Two standard tests, the **Charpy** and **Izod**, measure the **impact energy** (the energy required to fracture a test piece under an impact load), also called the **notch toughness**.

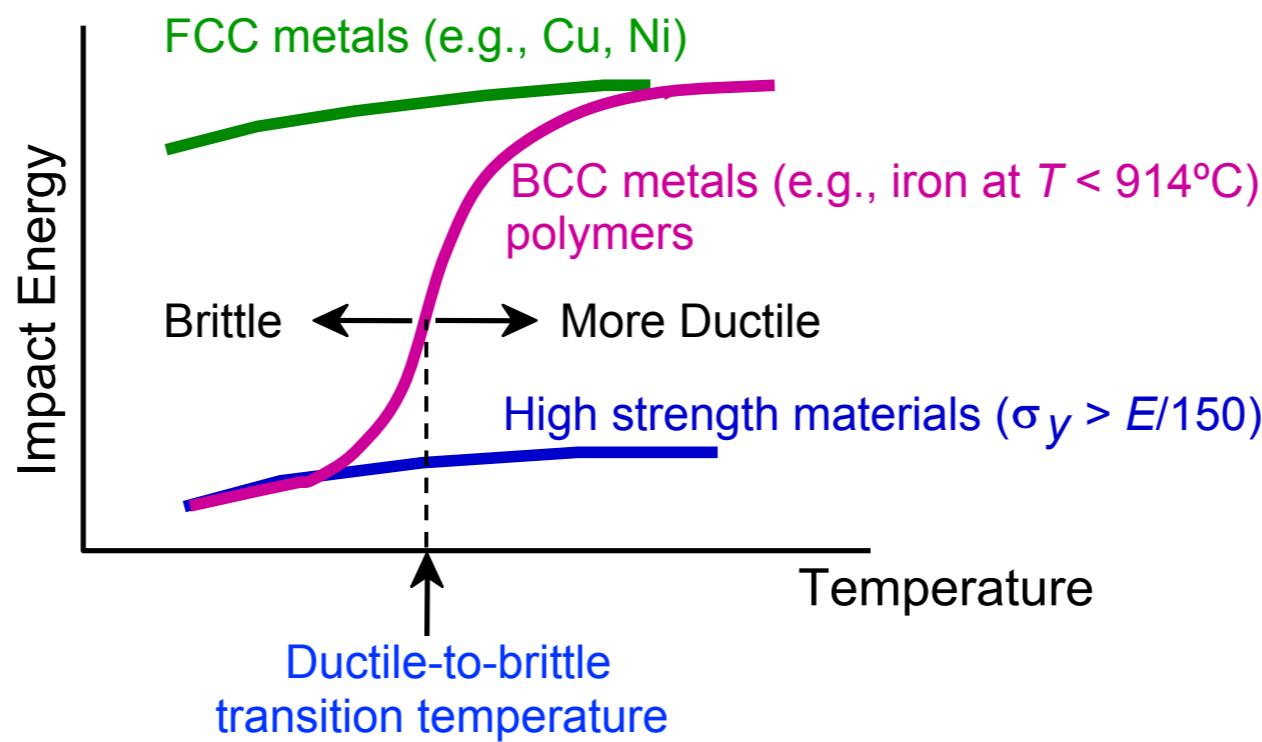


Ductile to brittle transition

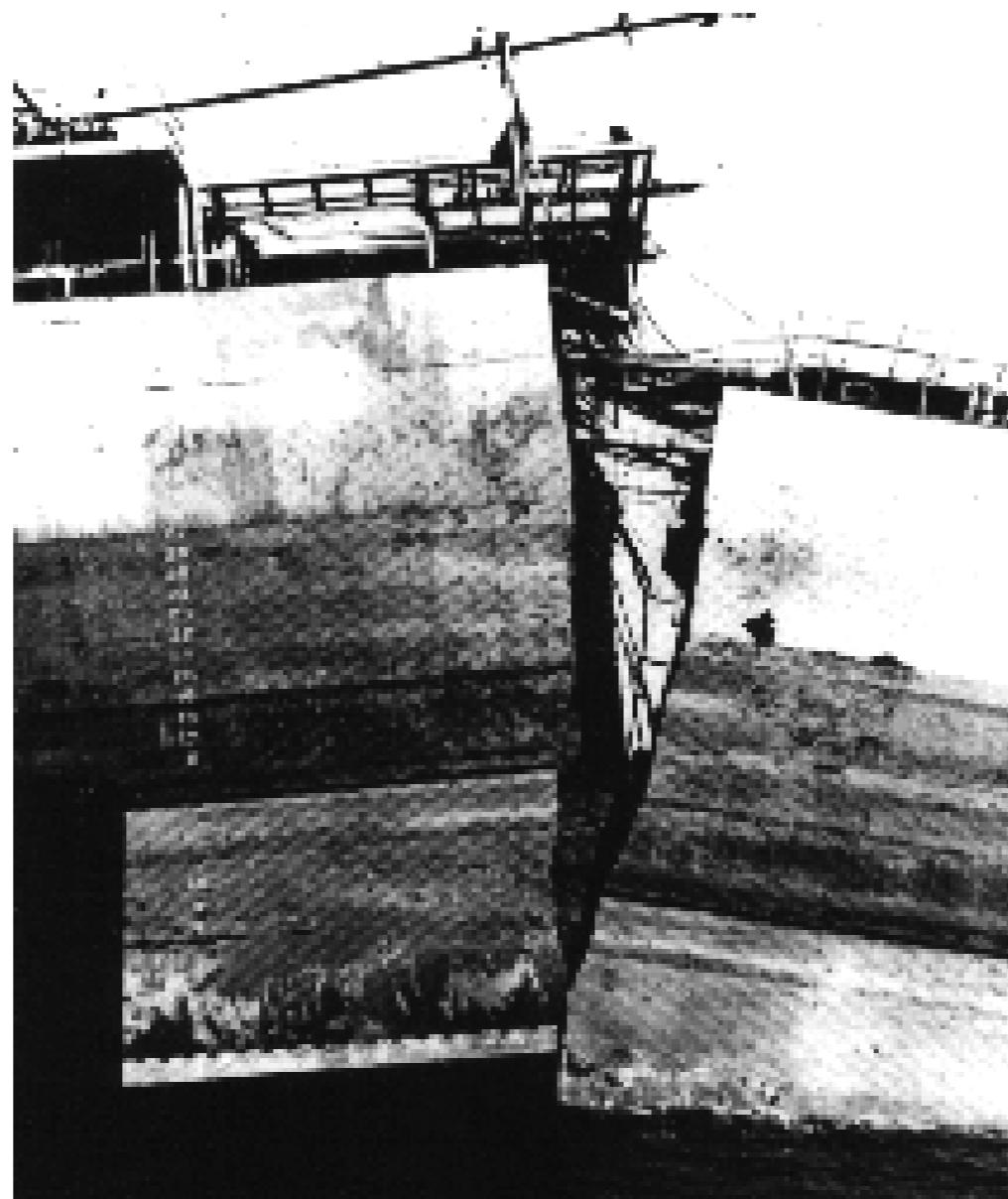
As temperature decreases a ductile material can become brittle - **ductile-to-brittle transition**

Alloying usually increases the ductile-to-brittle transition temperature. FCC metals remain ductile down to very low temperatures. For ceramics, this type of transition occurs at much higher temperatures than for metals.

The ductile-to-brittle transition can be measured by impact testing: the impact energy needed for fracture drops suddenly over a relatively narrow temperature range – temperature of the ductile-to-brittle transition.



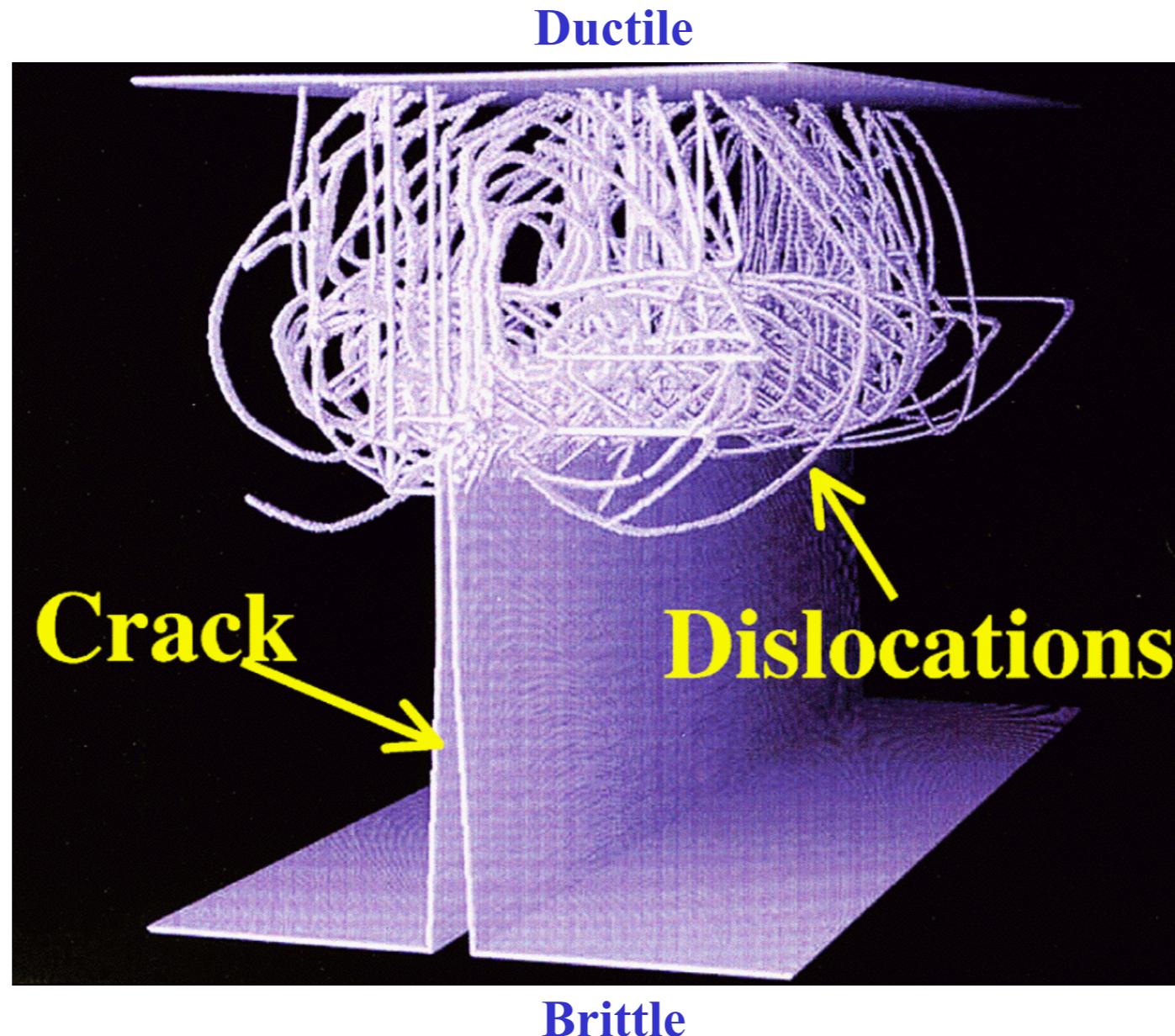
Ductile to brittle transition



Low temperatures can severely embrittle steels. The Liberty ships, produced in great numbers during the WWII were the first all-welded ships. A significant number of ships failed by catastrophic fracture. Fatigue cracks nucleated at the corners of square hatches and propagated rapidly by brittle fracture.

Dynamic brittle to ductile transition

(from molecular dynamics simulation of crack propagation)



V. Bulatov et al., Nature 391, #6668, 669 (1998)

Fatigue

(Failure under fluctuating / cyclic stresses)

Under fluctuating / cyclic stresses, failure can occur at loads considerably lower than tensile or yield strengths of material under a static load: **Fatigue**

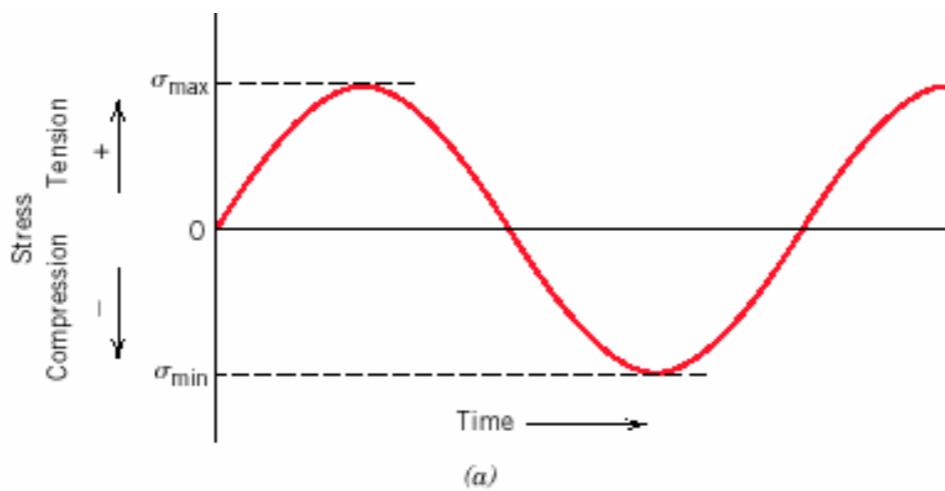
Estimated to causes 90% of all failures of metallic structures (bridges, aircraft, machine components, etc.)

Fatigue failure is brittle-like (relatively little plastic deformation) - even in normally ductile materials. Thus sudden and catastrophic!

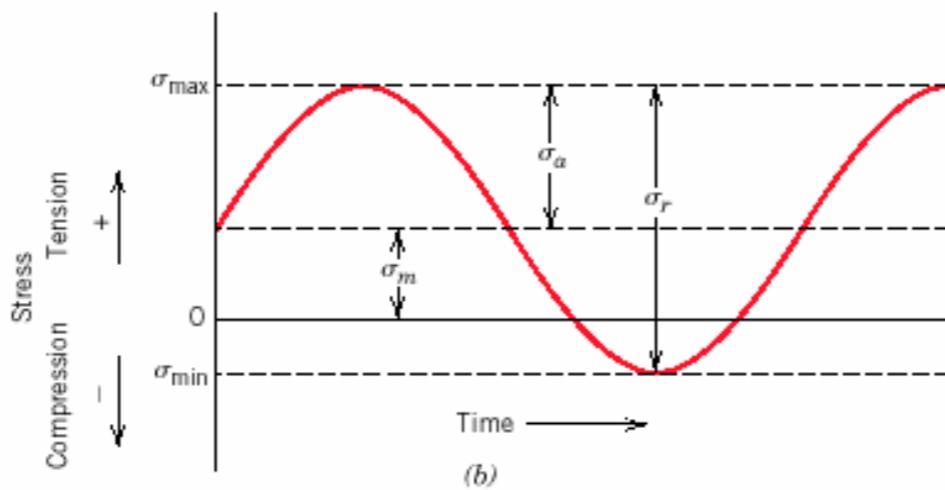
Applied stresses causing fatigue may be axial (tension or compression), flexural (bending) or torsional (twisting).

Fatigue failure proceeds in three distinct stages: crack initiation in the areas of stress concentration (near stress raisers), incremental crack propagation, final catastrophic failure.

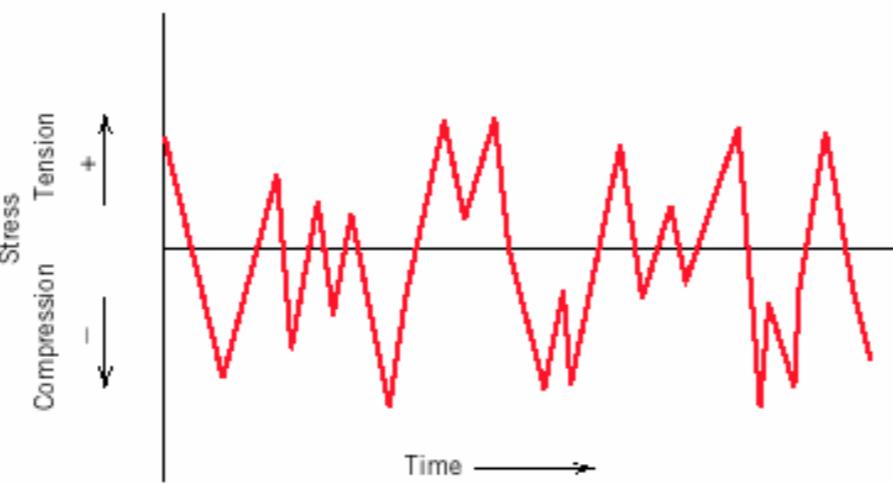
Fatigue: cyclic stress-I



**Periodic and
symmetrical
about zero
stress**



**Periodic and
asymmetrical
about zero
stress**



**Random
stress
fluctuations**

Fatigue: cyclic stress-II

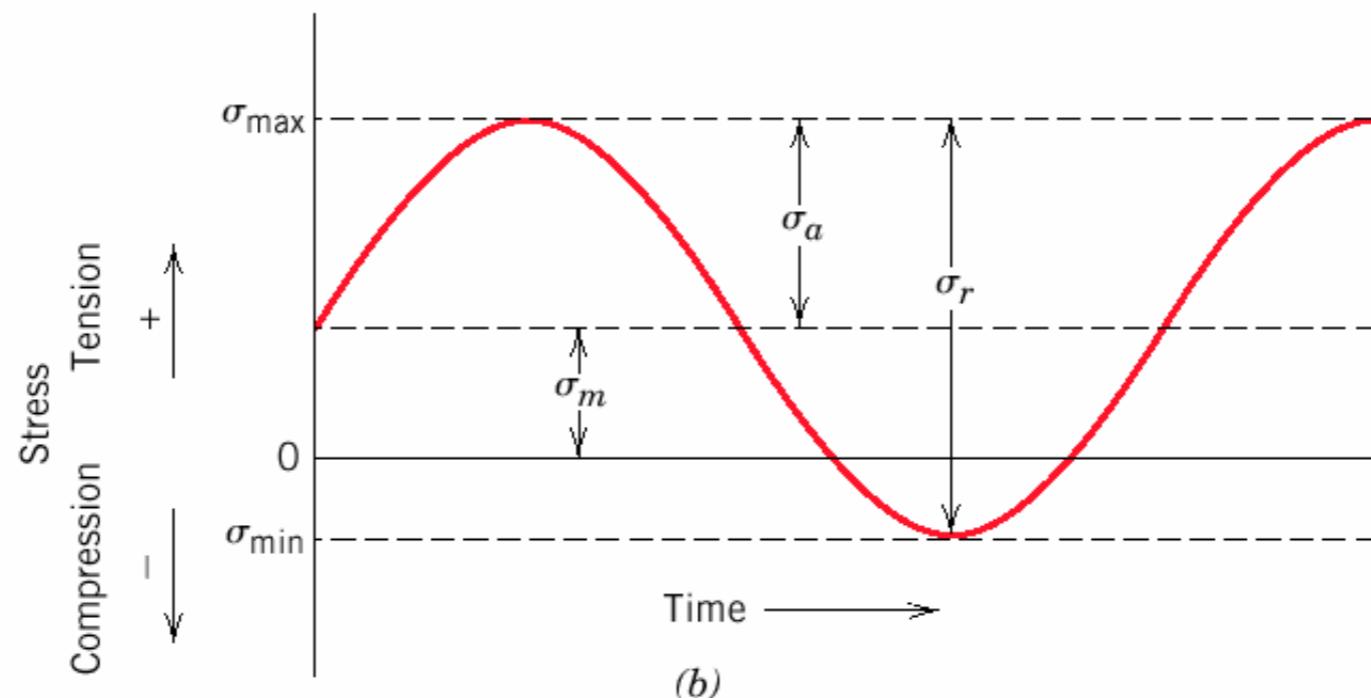
Cyclic stresses are characterized by maximum, minimum and mean stress, the range of stress, the stress amplitude, and the stress ratio

Mean stress: $\sigma_m = (\sigma_{\max} + \sigma_{\min}) / 2$

Range of stress: $\sigma_r = (\sigma_{\max} - \sigma_{\min})$

Stress amplitude: $\sigma_a = \sigma_r/2 = (\sigma_{\max} - \sigma_{\min}) / 2$

Stress ratio: $R = \sigma_{\min} / \sigma_{\max}$

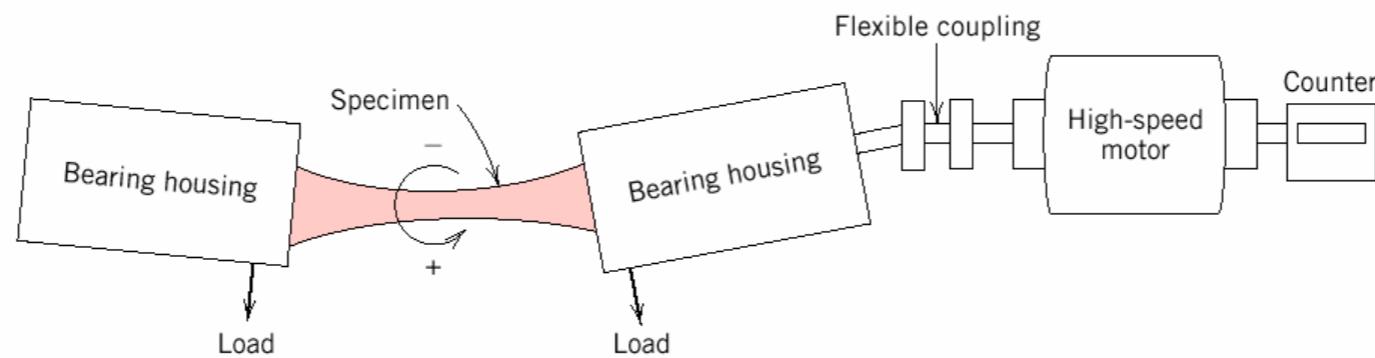


Remember the convention that tensile stresses are positive, compressive stresses are negative

Fatigue: S—N curve-I

(stress — number of cycles to failure)

Fatigue properties of a material (S-N curves) are tested in rotating-bending tests in fatigue testing apparatus:

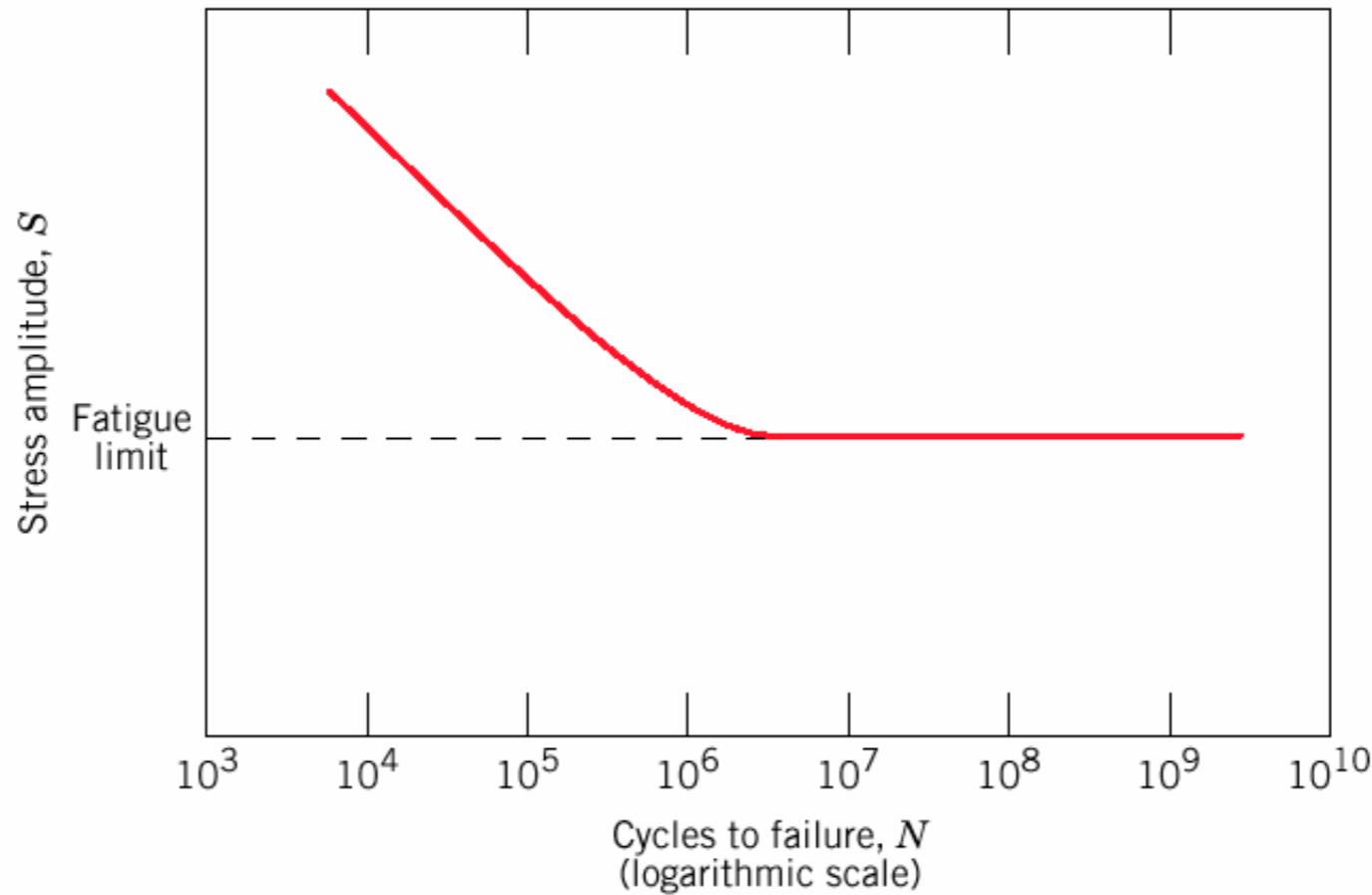


Result is commonly plotted as S (stress) vs. N (number of cycles to failure)

Low cycle fatigue: high loads, plastic and elastic deformation

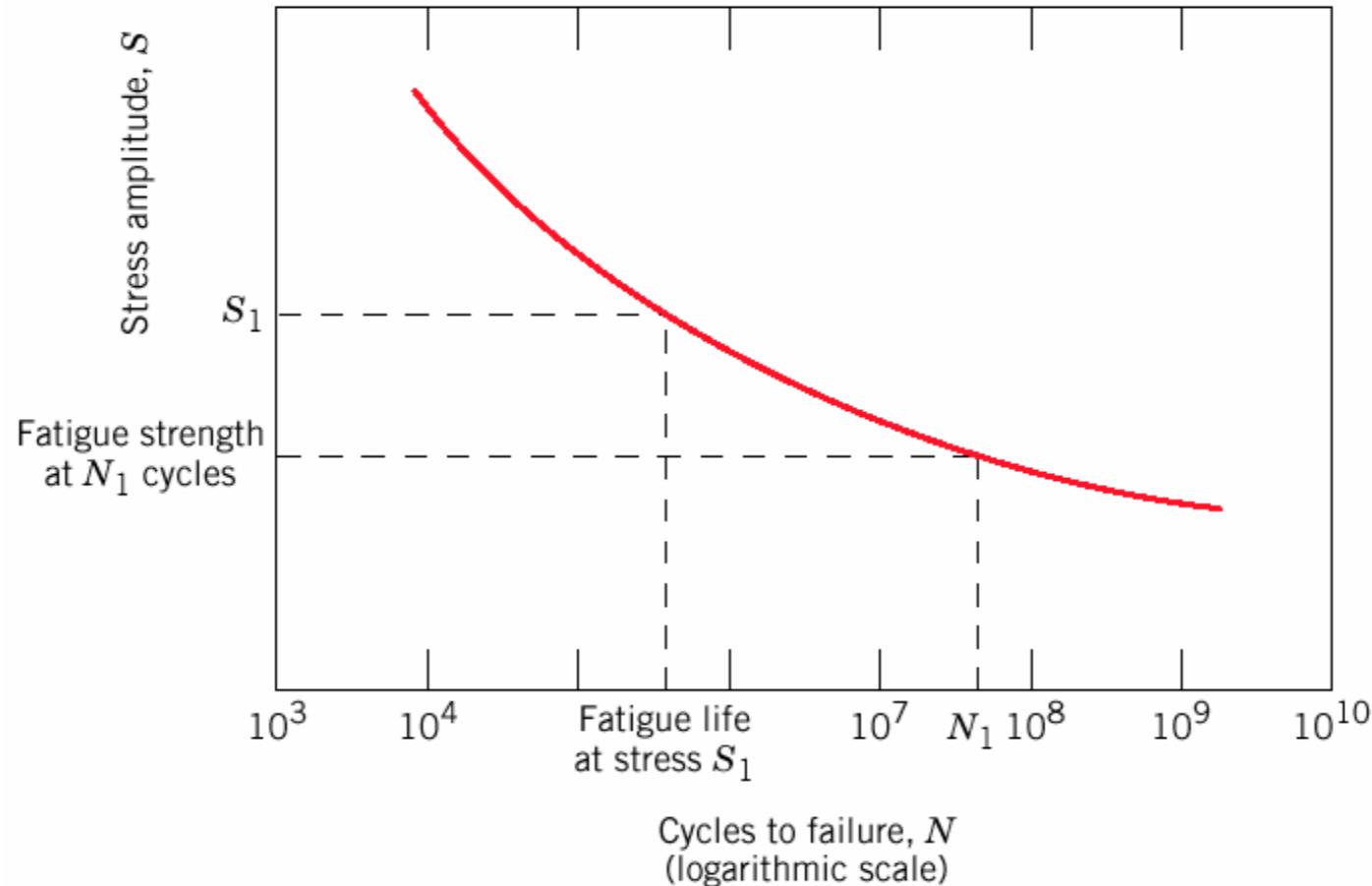
High cycle fatigue: low loads, elastic deformation ($N > 10^5$)

Fatigue: S—N curve-II



Fatigue limit (endurance limit) occurs for some materials (e.g. some Fe and Ti alloys). In this case, the S—N curve becomes horizontal at large N . The fatigue limit is a maximum stress amplitude below which the material never fails, no matter how large the number of cycles is.

Fatigue: S—N curve-III



In most alloys, S decreases continuously with N . In this cases the fatigue properties are described by

Fatigue strength: stress at which fracture occurs after a specified number of cycles (e.g. 10^7)

Fatigue life: Number of cycles to fail at a specified stress level

Fatigue: crack propagation and nucleation-I

Three stages of fatigue failure:

1. crack initiation in the areas of stress concentration (near stress raisers)
2. incremental crack propagation
3. final rapid crack propagation after crack reaches critical size

The total number of cycles to failure is the sum of cycles at the first and the second stages:

$$N_f = N_i + N_p$$

N_f : Number of cycles to failure

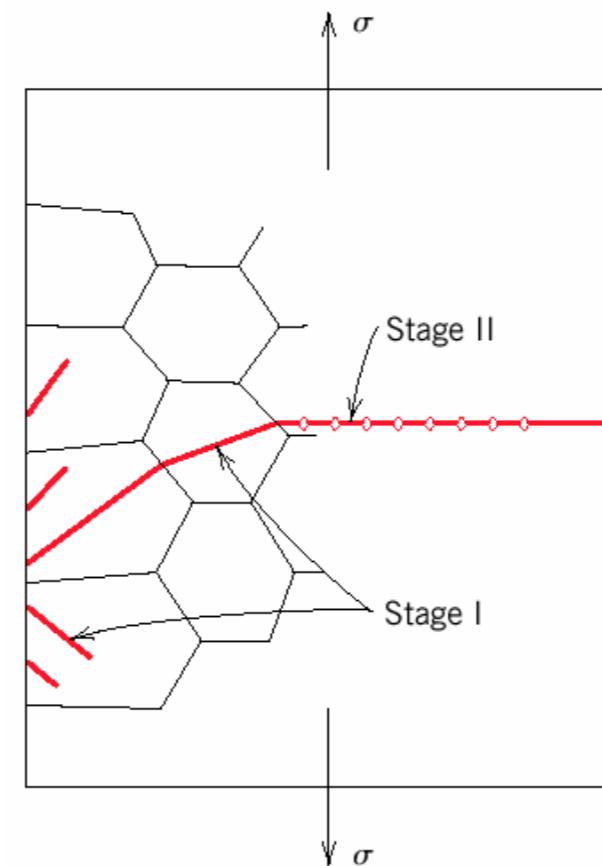
N_i : Number of cycles for crack initiation

N_p : Number of cycles for crack propagation

High cycle fatigue (low loads): N_i is relatively high. With increasing stress level, N_i decreases and N_p dominates

Fatigue: crack propagation and nucleation-II

- Crack initiation at the sites of stress concentration (microcracks, scratches, indents, interior corners, dislocation slip steps, etc.). Quality of surface is important.
- Crack propagation
 - Stage I: initial slow propagation along crystal planes with high resolved shear stress. Involves just a few grains, and has flat fracture surface
 - Stage II: faster propagation perpendicular to the applied stress. Crack grows by repetitive blunting and sharpening process at crack tip. Rough fracture surface.
- Crack eventually reaches critical dimension and propagates very rapidly

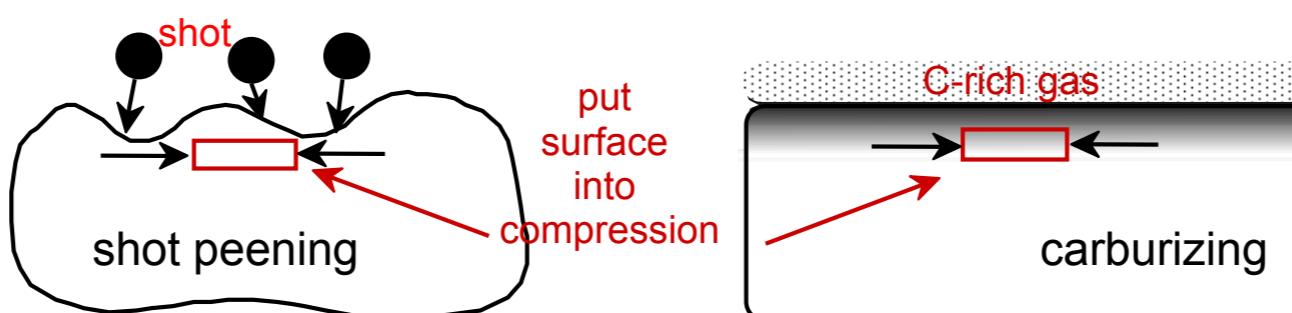


Factors affecting fatigue life-I

- Magnitude of stress (mean, amplitude...)
- Quality of the surface (scratches, sharp transitions).

Solutions:

- Polishing (removes machining flaws etc.)
- Introducing compressive stresses (compensate for applied tensile stresses) into thin surface layer by “Shot Peening”- firing small shot into surface to be treated. High-tech solution - ion implantation, laser peening.
- Case Hardening - create C- or N- rich outer layer in steels by atomic diffusion from the surface. Makes harder outer layer and also introduces compressive stresses
- Optimizing geometry - avoid internal corners, notches etc.



Factors affecting fatigue life-II

- **Thermal Fatigue.** Thermal cycling causes expansion and contraction, hence thermal stress, if component is restrained.

Solutions:

- eliminate restraint by design
- use materials with low thermal expansion coefficients

- **Corrosion fatigue.** Chemical reactions induce pits which act as stress raisers. Corrosion also enhances crack propagation.

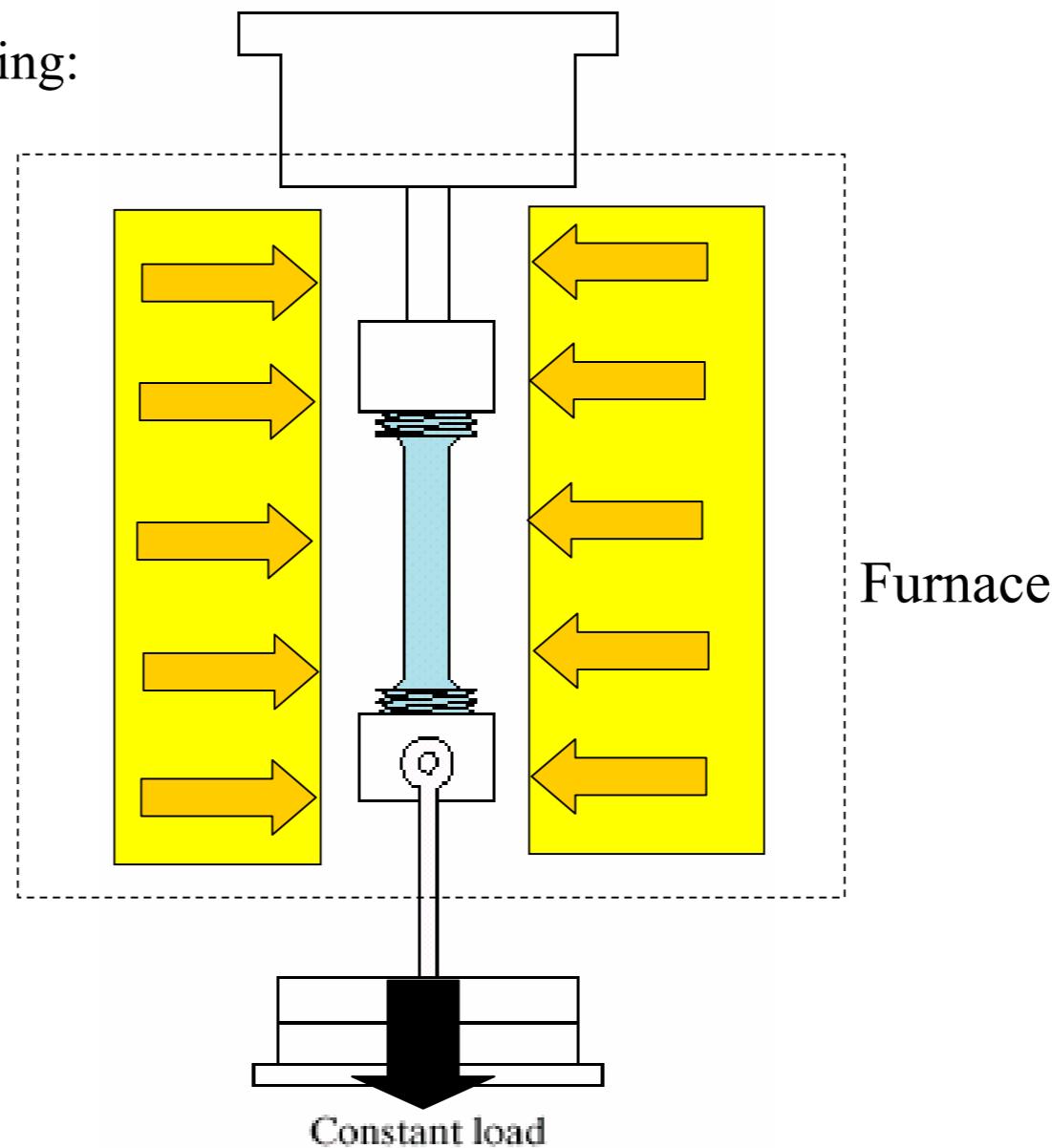
Solutions:

- decrease corrosiveness of medium, if possible
- add protective surface coating
- add residual compressive stresses

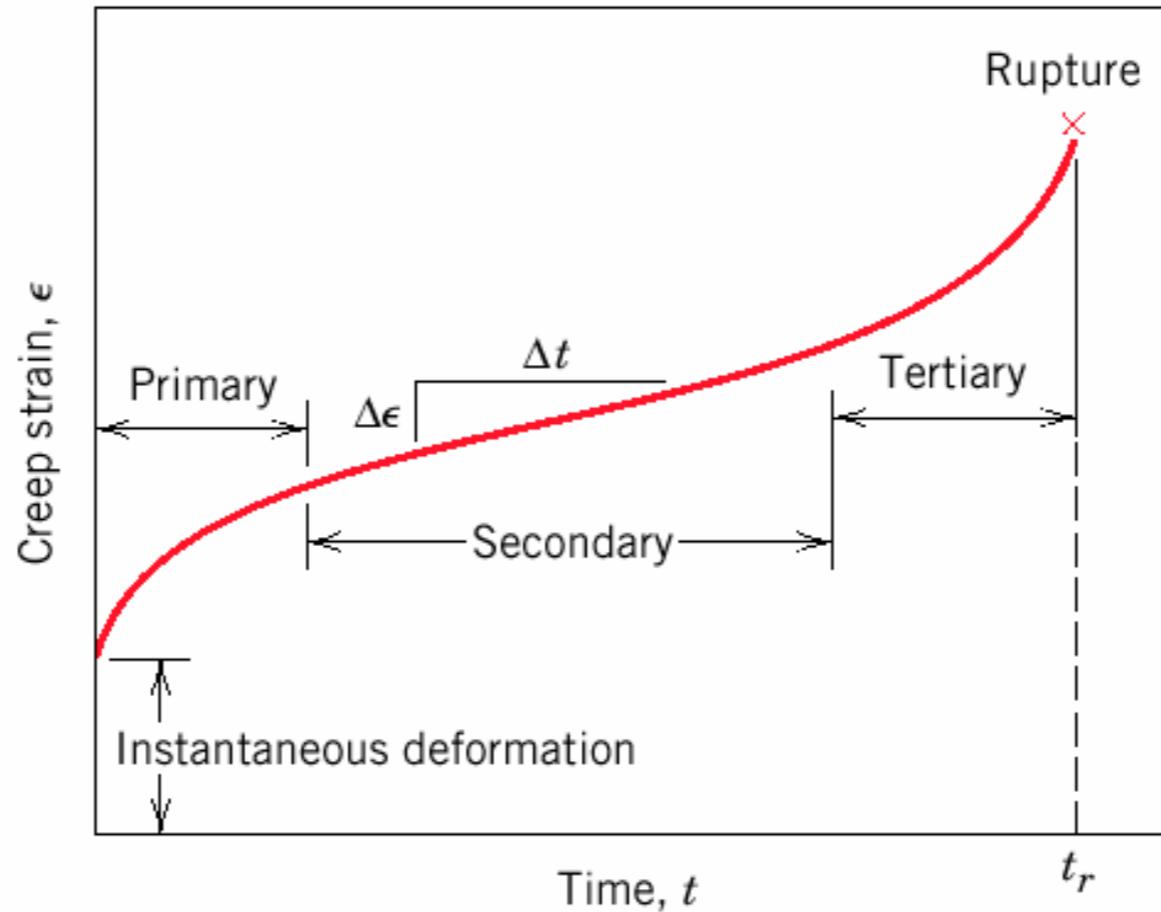
Creep

Creep is a **time-dependent and permanent** deformation of materials when subjected to a constant load at a **high temperature** ($> 0.4 T_m$). Examples: turbine blades, steam generators.

Creep testing:



Stages of creep

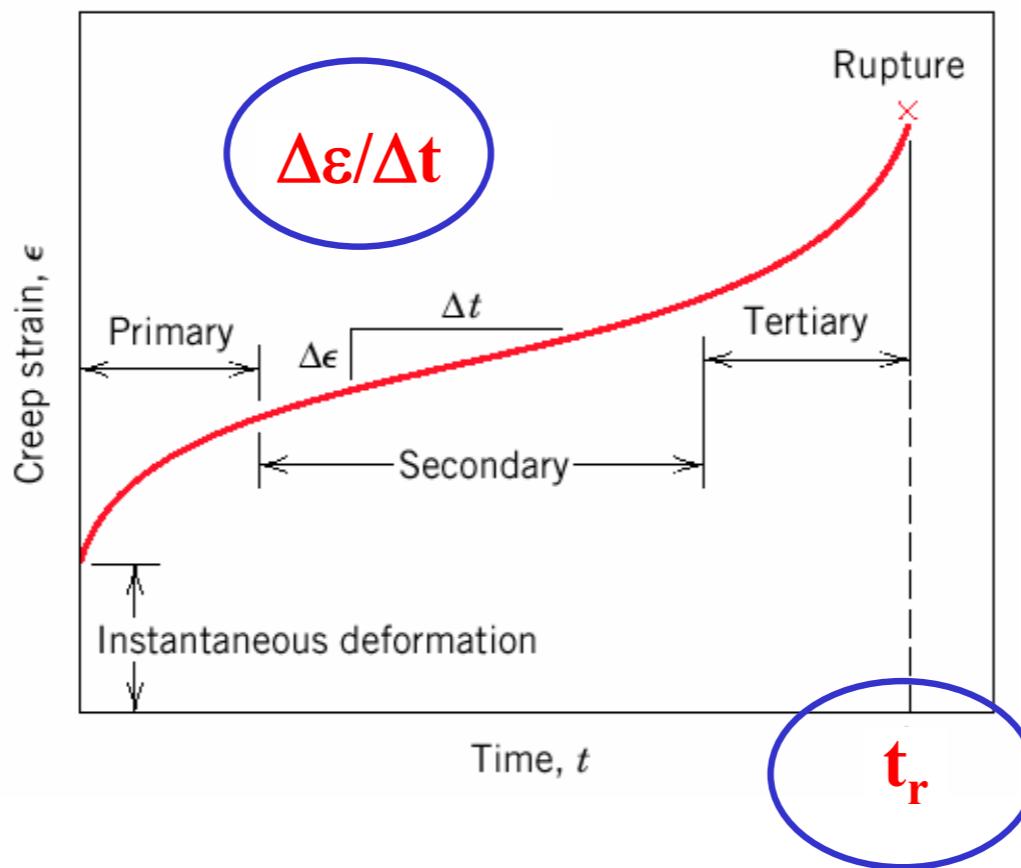


1. **Instantaneous deformation**, mainly elastic.
2. **Primary/transient creep**. Slope of strain vs. time decreases with time: work-hardening
3. **Secondary/steady-state creep**. Rate of straining is constant: balance of work-hardening and recovery.
4. **Tertiary**. Rapidly accelerating strain rate up to failure: formation of internal cracks, voids, grain boundary separation, necking, etc.

Parameters of creep behavior

The stage of **secondary/steady-state creep** is of longest duration and the **steady-state creep rate** $\dot{\epsilon}_s = \Delta\epsilon / \Delta t$ is the most important parameter of the creep behavior in long-life applications.

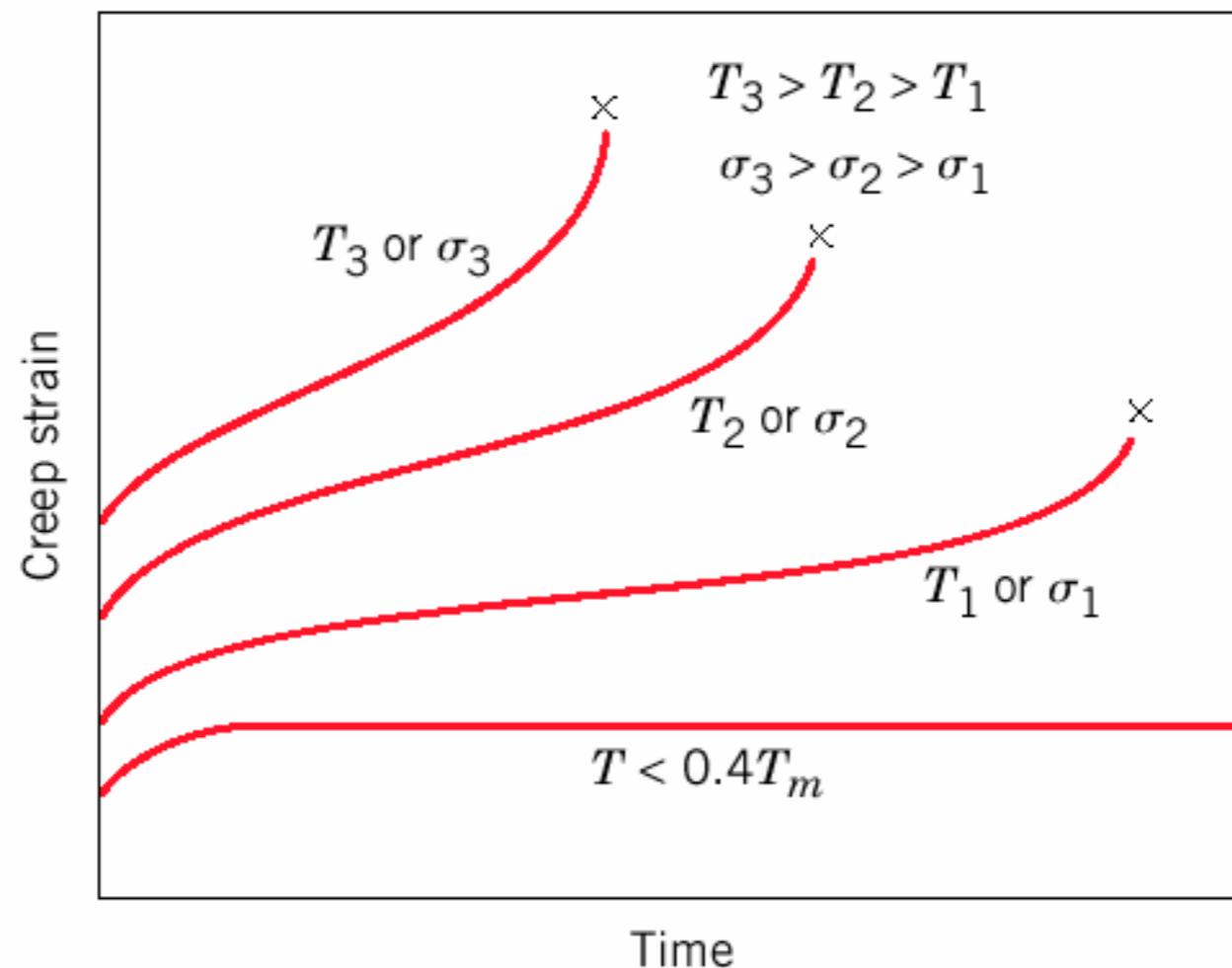
Another parameter, especially important in short-life creep situations, is **time to rupture, or the rupture lifetime, t_r .**



Creep: Stress and temperature effect

With increasing stress or temperature:

- The instantaneous strain increases
- The steady-state creep rate increases
- The time to rupture decreases



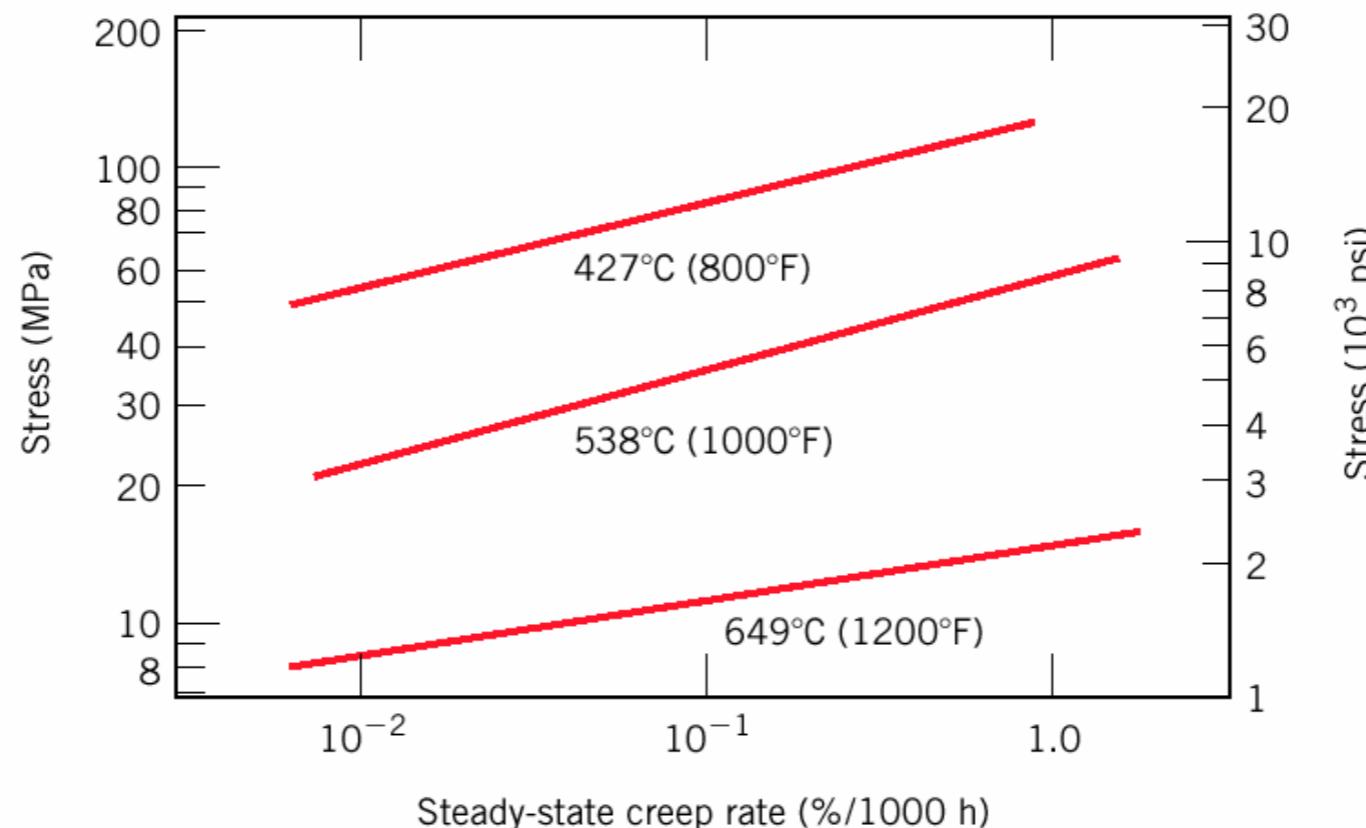
Creep: Stress and temperature effect

The stress/temperature dependence of the steady-state creep rate can be described by

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

where Q_c is the activation energy for creep, K_2 and n are material constants.

(Remember the Arrhenius dependence on temperature for thermally activated processes that we discussed for diffusion)

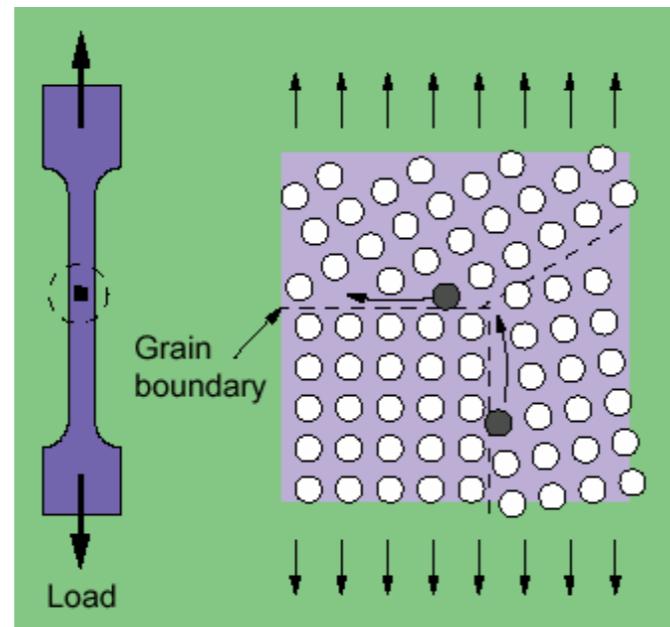


Mechanism of Creep

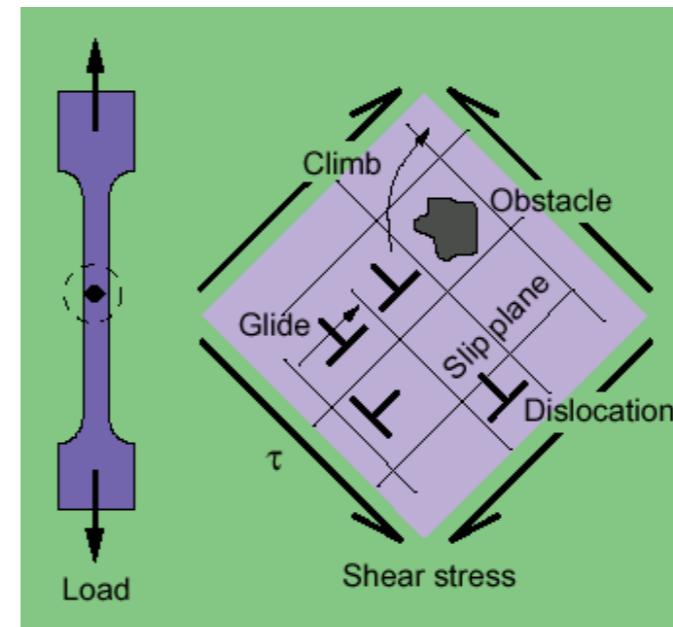
Different mechanisms are responsible for creep in different materials and under different loading and temperature conditions. The mechanisms include

- Stress-assisted vacancy diffusion
- Grain boundary diffusion
- Grain boundary sliding
- Dislocation motion

Different mechanisms result in different values of n , Q_c .



Grain boundary diffusion



Dislocation glide and climb

High temperature materials

(turbines in jet engines, hypersonic airplanes, nuclear reactors, etc.)

Creep is generally minimized in materials with:

- ✓ High melting temperature
- ✓ High elastic modulus
- ✓ Large grain sizes (inhibits grain boundary sliding)

Following alloys are especially resilient to creep:

- ✓ Stainless steels
- ✓ Refractory metals (containing elements of high melting point, like Nb, Mo, W, Ta)
- ✓ “Superalloys” (Co, Ni based: solid solution hardening and secondary phases)

Summary

Make sure you understand language and concepts:

- Brittle fracture
- Corrosion fatigue
- Creep
- Ductile fracture
- Ductile-to-brittle transition
- Fatigue
- Fatigue life
- Fatigue limit
- Fatigue strength
- Impact energy
- Intergranular fracture
- Stress raiser
- Thermal fatigue
- Transgranular fracture

References

- University of Tennessee
- University of Virginia
- Mechanical Metallurgy, Dieter G. 3rd Edition