Unit 6: Mechanical properties of materials

- Concept of stress and strain,
- elastic deformation,
- plastic deformation,
- strengthening,
- Hardness,
- mechanical properties of metals, ceramics and polymers.

Mechanical properties of materials

- Many materials, when in service, are subjected to forces or loads; examples include the aluminum alloy from which an airplane wing is constructed and the steel in an automobile axle.

- In such situations it is necessary to know the characteristics of the material and to design the member from which it is made such that any resulting *deformation* will not be *excessive and fracture will not occur*. The mechanical behavior of a material reflects the relationship between *its response or deformation to an applied load or force*.

- Key mechanical design properties are *stiffness, strength, hardness, ductility, and toughness*.

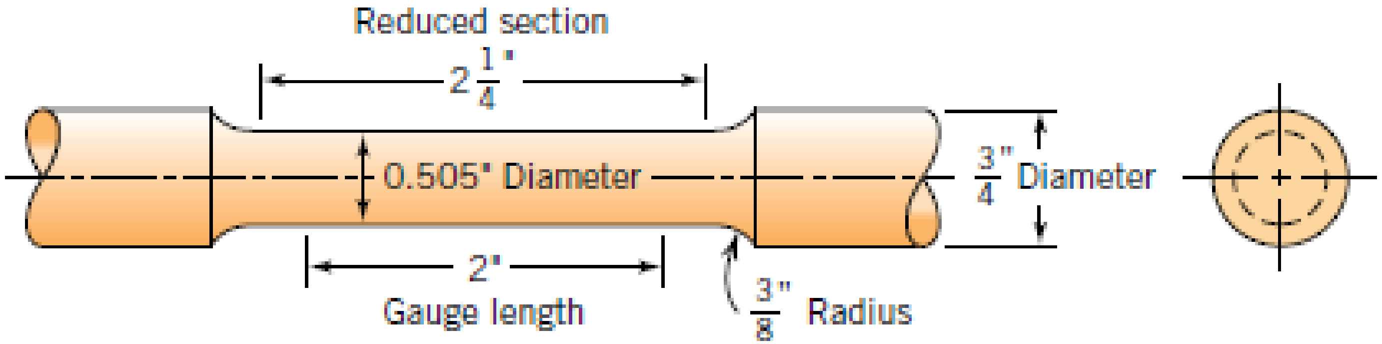
- The mechanical properties of materials are ascertained by performing *carefully designed laboratory experiments* that replicate as nearly as possible the service conditions.

Concept of Stress and Strain

- The mechanical behavior may be ascertained by a simple stress–strain test; these are most commonly conducted for metals at room temperature. There are three principal ways in which a load may be applied: namely, *tension, compression, and shear*

Tension Tests

- One of the most common mechanical stress–strain tests is performed in ***tension***. The tension test can be used to ascertain several mechanical properties of materials that are important in *design*. A specimen is deformed, usually to fracture, with a gradually increasing tensile load that is applied uniaxially along the long axis of a specimen. A *standard tensile specimen* is shown in Figure



The output of such a tensile test is recorded as load or force versus elongation

Engineering stress is defined by the relationship

$$\sigma = \frac{F}{A_0}$$

Engineering strain is defined according to

$$\varepsilon = \frac{\Delta l}{l_0}$$

Compression Tests

- A compression test is conducted in a manner similar to the tensile test, except that the force is compressive and the specimen contracts along the direction of the stress. Above equations are utilized to compute compressive stress and strain, respectively.

- Tensile tests are more common because they are easier to perform; also, for most materials used in structural applications, very little additional information is obtained from compressive tests.

- Compressive tests are used when a material's behavior under large and permanent (i.e., plastic) strains is desired, as in manufacturing applications, or when the material is brittle in tension.

Elastic Deformation

Stress-Strain Behavior

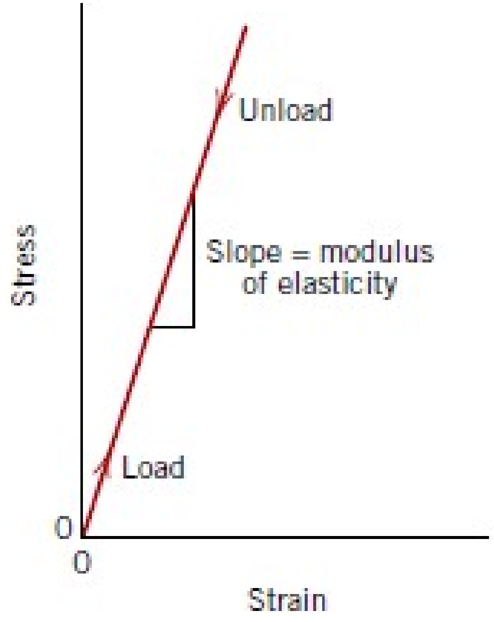
- The degree to which a structure deforms or strains depends on the magnitude of an imposed stress. For most metals that are stressed in tension and at relatively low levels, stress and strain are proportional to each other through the relationship

$$\sigma = E\,\epsilon$$

- This is known as **Hooke's law**, and the constant of proportionality *E* (GPa or psi) is the **modulus of elasticity**, or **Young's modulus**. For most typical metals the magnitude of this modulus ranges between 45 GPa to 400 GPa

- Deformation in which stress and strain are proportional is called elastic deformation; a plot of stress (ordinate) versus strain (abscissa) results in a linear relationship.

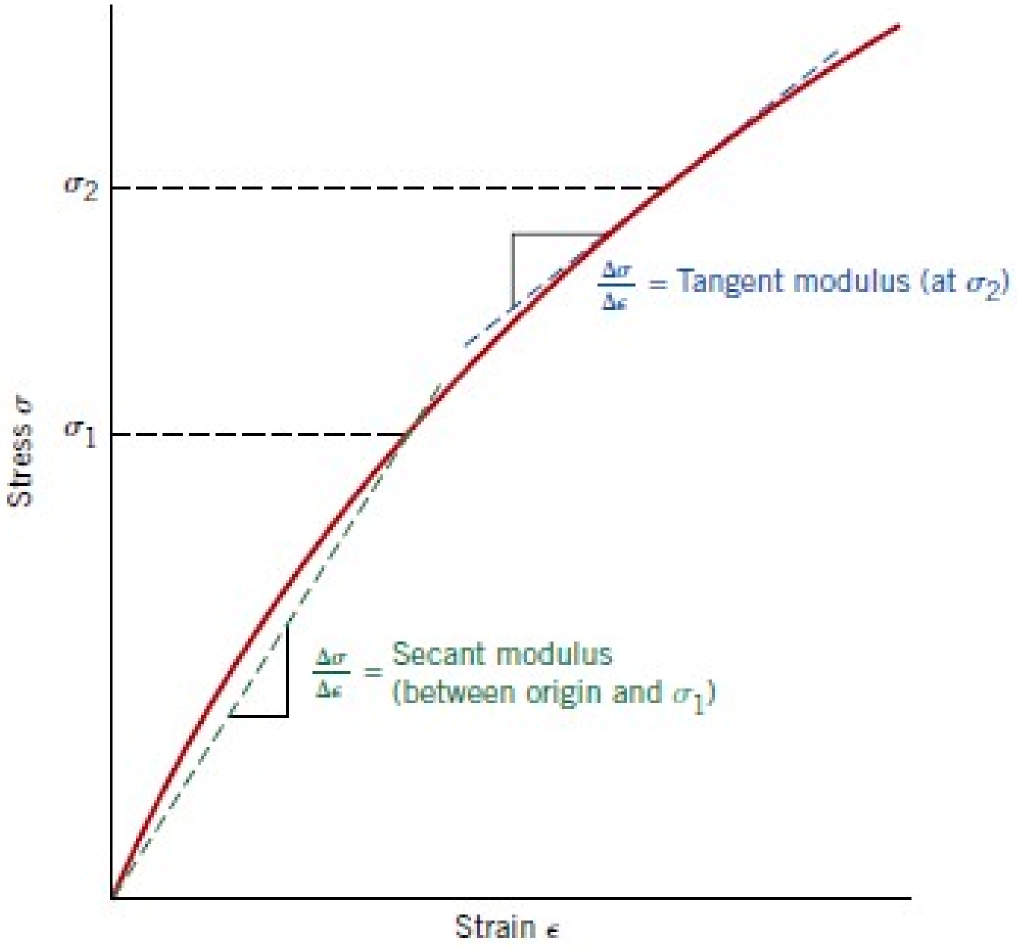
- The slope of this linear segment corresponds to the modulus of elasticity *E*. *This modulus represents stiffness, or a material's resistance to elastic deformation. The greater the modulus, the stiffer the material.*



- There are some materials (e.g., gray cast iron, concrete, and many polymers) for which this elastic portion of the stress–strain curve is not linear

- For this nonlinear behavior, either tangent or secant modulus is normally used.

- Tangent modulus is taken as the slope of the stress–strain curve at some specified level of stress, whereas secant modulus represents the slope of a secant drawn from the origin to some given point of the curve

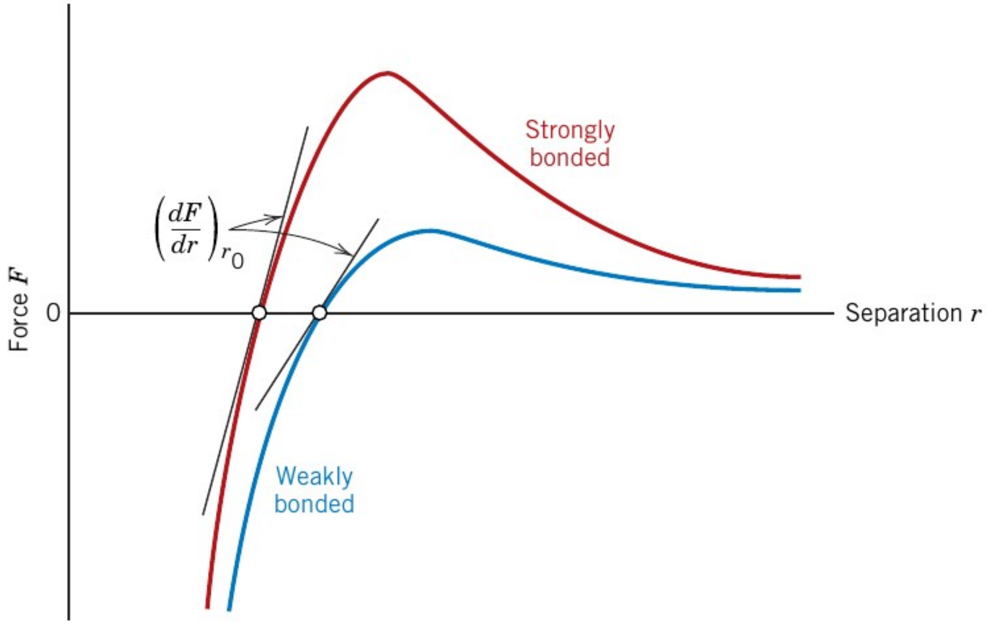


Schematic stress–strain diagram showing nonlinear elastic behavior and how secant and tangent moduli are determined.

- On an atomic scale, macroscopic elastic strain is manifested as small changes in the interatomic spacing and the stretching of interatomic bonds.

- Magnitude of the modulus of elasticity is a measure of the resistance to separation of adjacent atoms, that is, the interatomic bonding forces.

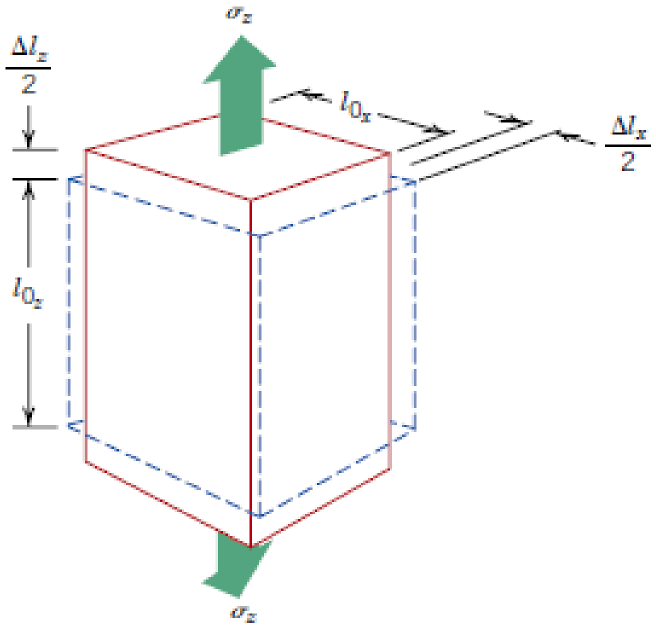
- this modulus is proportional to the slope of the interatomic force–separation curve at the equilibrium spacing:



$$E \propto \left(\frac{dF}{dr}\right)_{r_0}$$

Elastic Properties of Materials

- When a tensile stress is imposed on a metal specimen, an elastic elongation and accompanying strain result in the direction of the applied load.



- As a result of this elongation, there will be constrictions in the lateral (*x* and *y*) directions perpendicular to the applied stress; from these contractions, the compressive strains may be determined.

- A parameter termed Poisson's ratio is defined as the ratio of the lateral and axial strains,

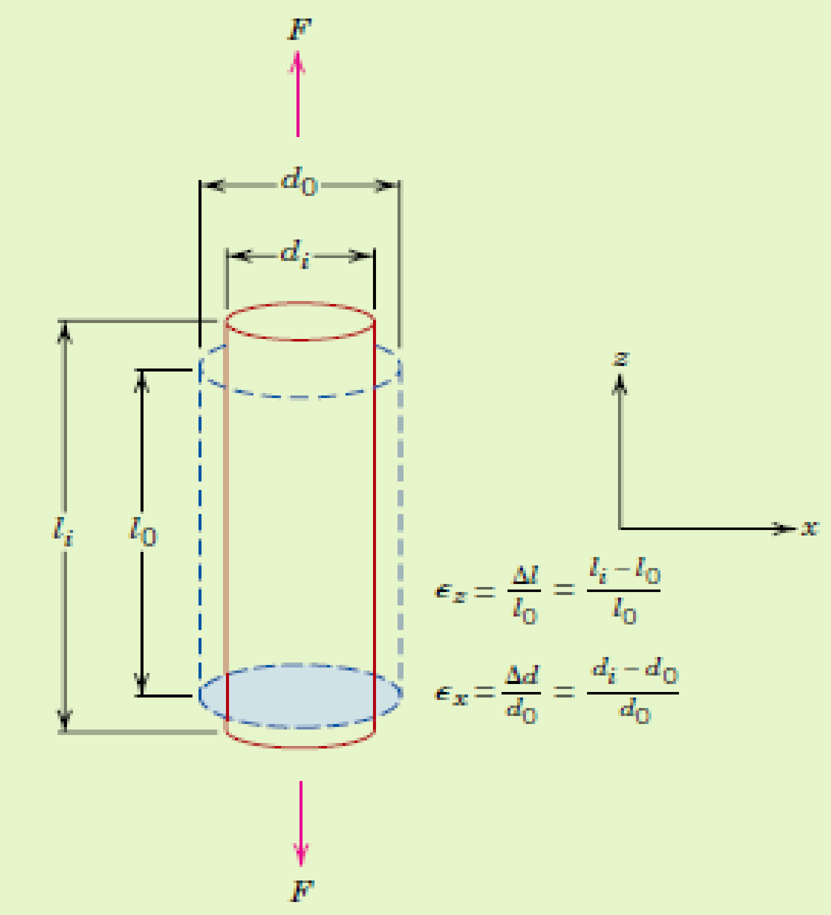
$$\vartheta = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z}$$

- For many metals and other alloys, values of Poisson's ratio range between 0.25 and 0.35.

- For isotropic materials, shear and elastic moduli are related to each other and to Poisson's ratio according to

$$E = 2G(1+\vartheta)$$

Isotropic materials are materials that have the same properties when tested in different directions.



Numerical problem:

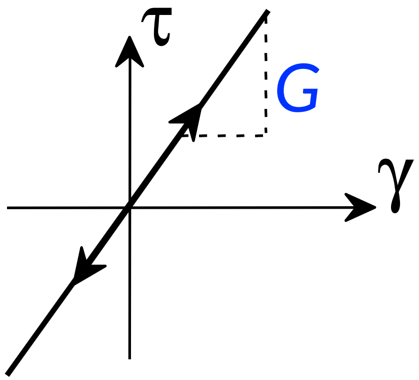
- A tensile stress is to be applied along the long axis of a cylindrical brass rod that has a diameter of 10 mm.

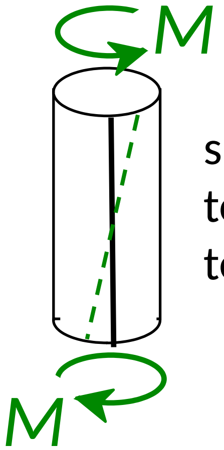
  Determine the magnitude of the load required to produce a 2.5×10^{-3} mm change in diameter if the deformation is entirely elastic. Poisson's ratio for brass is 0.35 and elastic modulus is 97 GPa

Other Elastic Properties

- Elastic Shear modulus, G:

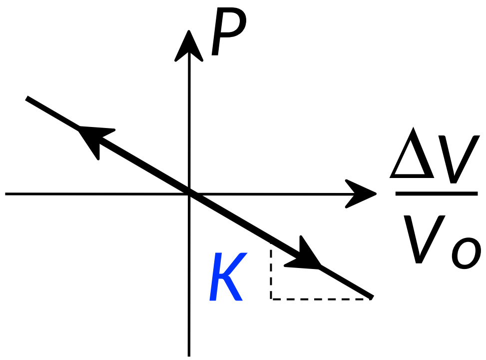
$$\tau = G\,\gamma$$

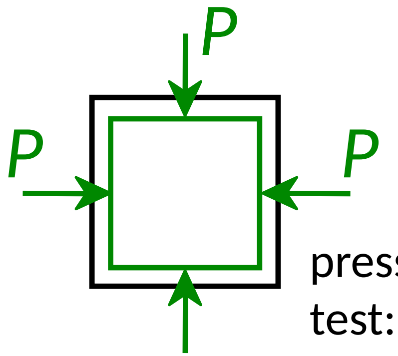




- Elastic Bulk modulus, K:

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





pressure test: Init. vol $=V_o$. Vol chg. $= \Delta V$

- Special relations for isotropic materials:

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

Plastic Deformation

- For most metallic materials, elastic deformation persists only to strains of about 0.005.

- As the material is deformed beyond this point, the stress is no longer proportional to strain (Hooke's law, ceases to be valid), and permanent, non-recoverable, or plastic deformation occurs.

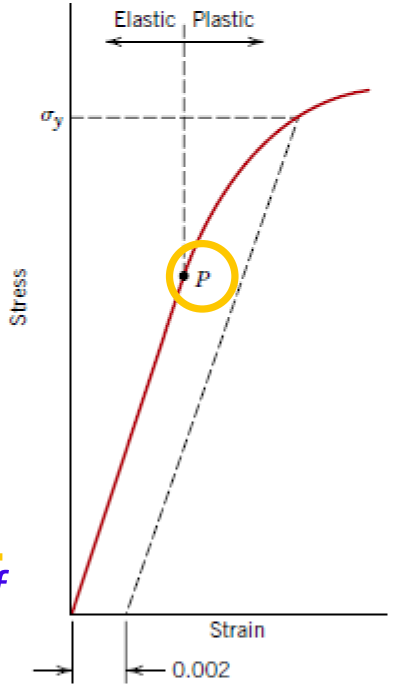
- From an atomic perspective, plastic deformation corresponds to the *breaking of bonds* with original atom neighbors and then *re-forming bonds with new neighbors* as large numbers of atoms or molecules move relative to one another; upon removal of the stress they do not return to their original positions.

- For crystalline solids, deformation is accomplished by means of *slip*, which involves the motion of dislocations.

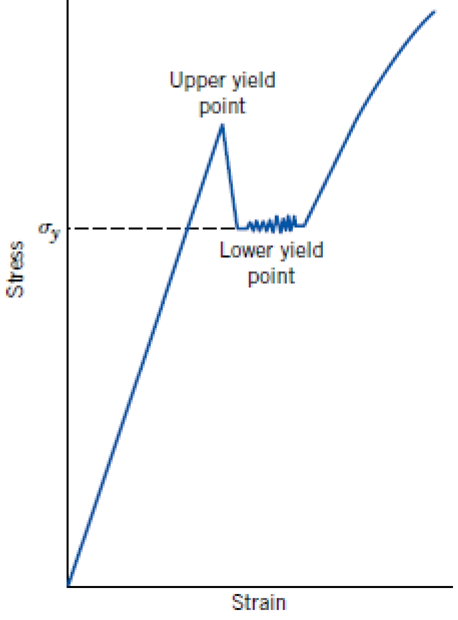
Yielding and Yield Strength

- It is the stress level at which plastic deformation begins, or where the phenomenon of *yielding* occurs

- For metals, the point of yielding may be determined as the *initial departure from linearity* of the stress–strain curve; this is sometimes called the *proportional limit,* as indicated by point *P* in Figure and represents the *onset of plastic deformation on a microscopic level*.



Yield-point phenomenon- e.g.- mild steel



- The position of this point *P is difficult to measure precisely*. As a consequence, a convention has been established wherein a straight line is constructed parallel to the elastic portion of the stress–strain curve at some specified strain offset, *usually 0.002*. The stress corresponding to the intersection of this line and the stress–strain curve is defined as the *yield strength*

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Stress-Stress Behavior

- One of the simplest test which can be performed to evaluate the mechanical properties of a material is the *Uniaxial Tension Test*.

- This is typically performed on a cylindrical specimen with a standard 'gauge length'. *(At constant temperature and strain rate).*

- Data acquired from such a test can be plotted as: (i) load-displacement, (ii) engineering stress- engineering strain, (iii) true stress- true strain.

- It is convenient to use Engineering Stress (s) and Engineering Strain (e) as we can divide the load and change in length by constant quantities (A_0 and L_0). Subscripts '0' refer to initial values and 'i' to instantaneous values.

Though this is simple test to conduct, a wealth of information about the mechanical behavior of a material can be obtained (Modulus of elasticity, ductility etc.)

Elastic Region: σ_y is the stress required to start plastic deformation. It is called the yield stress. From σ_y & on $\rightarrow$ plastic deformation starts.

Stage I: Primary slip systems are active.

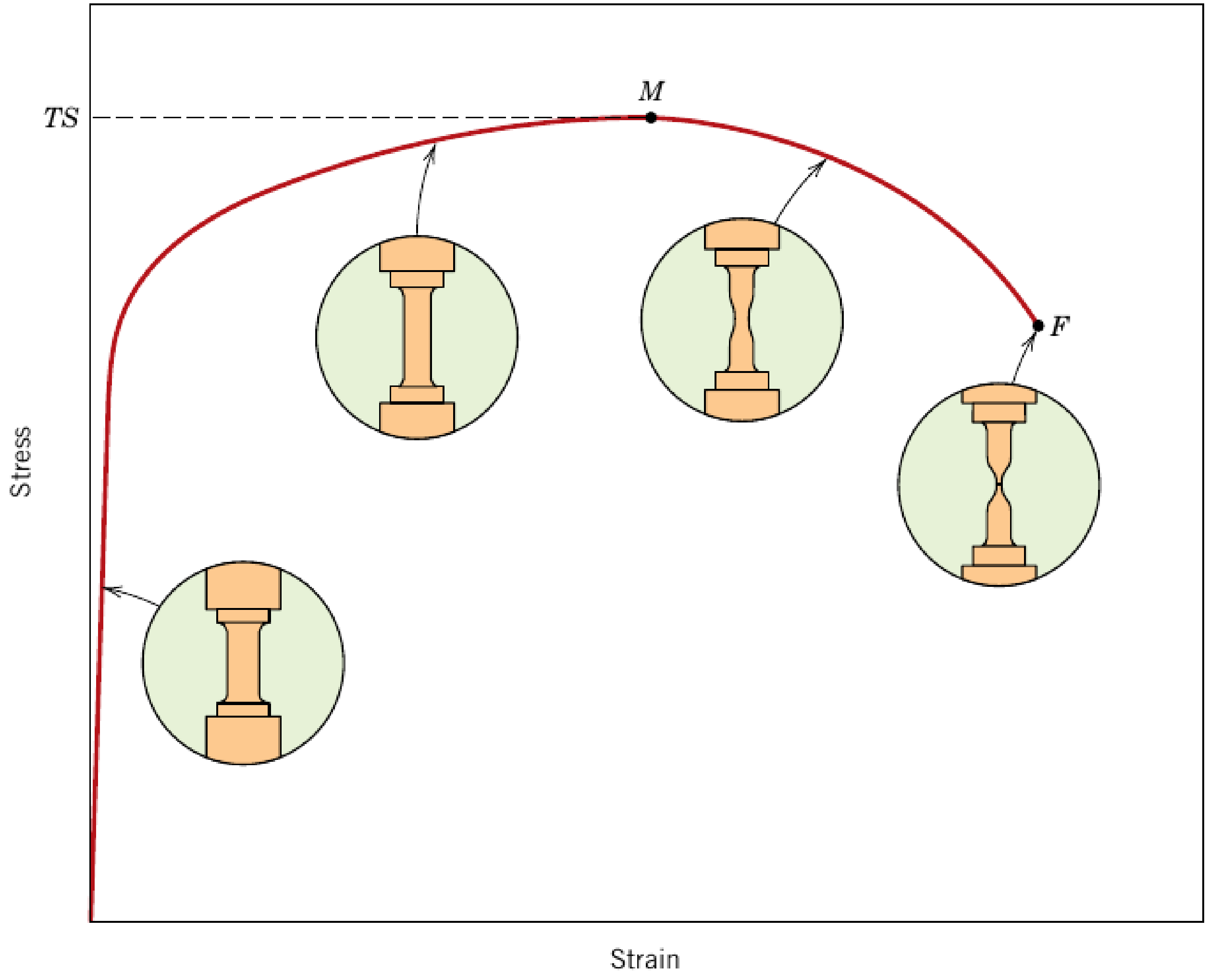
Slip planes are parallel to each other and only these parallel planes will slip and they do not intersect themselves, i.e. dislocations are moving along parallel planes.

Stage II: Other dislocations will start to move along intersecting planes (more than one slip system becomes active). Therefore they form barriers to one another's motion. It becomes harder to further deform the material. This stage is known as Work Hardening Stage.

Stage III: The geometry of the planes have so changed that the planes will accelerately slip and failure will occur.

Schematic σ-ε curves

- These are simplified schematics which are close to the curves obtained for some metallic materials like Al, Cu etc. (polycrystalline materials at room temperature).
- Most ceramics are brittle with very little plastic deformation.
- Even these diagrams are not to scale as the strain at yield is ~0.001 ($e_{elastic}$ ~10^{-3})
  [E is measured in GPa and σ_y in Mpa, ε thus giving this small strains]
  σ the linear portion is practically vertical and stuck to the Y-axis (when $e_{fracture}$ and $e_{elastic}$ is drawn to the same scale).



Information gained from the test:
i) Young's modulus
ii) Yield stress (or proof stress)
iii) Ultimate Tensile Stress (UTS)
iv) Fracture stress

Another measure of stress and strain

- True Stress (σ) and True Strain (ε) are defined wherein we use instantaneous values of length and area.

Engineering stress-strain vs true stress-strain

When the stress is calculated on the basis of the original area, it is called the engineering or nominal stress.

The nominal stress $\boxed{\sigma_n = P/A_0}$
where P is the force and A_0 the original area of cross section

The nominal strain, $\boxed{\varepsilon_n = (L-L_0)/L_0}$
where L is the length under force P, and L_0 is the original gauge length.

$$\varepsilon_t = ln(1+\varepsilon_n)$$

When the stress is calculated based on the instantaneous area at any instant of load, then it is the true stress.

$$True\,Stress\,(\sigma_T) = \frac{\text{Instantaneous load}}{\text{Instantaneous cross-sectional area}}$$

$$\boxed{(\sigma_T) = \frac{P}{A_i}}$$

True Strain (ε) is given as

$$\boxed{\varepsilon_t = \int_{L_0}^{L} \cdot \frac{dL}{L} = ln \frac{L}{L_0}}$$

If we assume that the volume change during plastic deformation can be neglected then we can write

True stress is given by: $$\boxed{\sigma_t = \frac{P}{A_i} = \frac{P\,L_i}{L_0\,A_0}}$$

New length can be expressed in terms of original length and change in length

Thus $$\sigma_t = \frac{P\left(L_0 + \Delta L\right)}{L_0\,A_0}$$

Or $$\sigma_t = \frac{P}{A_0}\left(\frac{L_0 + \Delta L}{L_0}\right)$$

Hence $$\sigma_t = \sigma_n\left(1 + \varepsilon_n\right)$$

- For some metals and alloys the region of the true stress–strain curve from the onset of plastic deformation to the point at which necking begins may be approximated by

$$\sigma_t = k\,\varepsilon_t^n$$

In this expression, *K* and *n* are constants; these values will vary from alloy to alloy and will also depend on the condition of the material (i.e., whether it has been plastically deformed, heat-treated, etc.). The parameter *n* is often termed the *strain-hardening exponent* and has a value less than unity. Values of *n* and *K* for several alloys

Tabulation of *n* and *K* Values

		K	
Material	*n*	*MPa*	*psi*
Low-carbon steel (annealed)	0.21	600	87,000
4340 steel alloy (tempered @ 315°C)	0.12	2650	385,000
304 stainless steel (annealed)	0.44	1400	205,000
Copper (annealed)	0.44	530	76,500
Naval brass (annealed)	0.21	585	85,000
2024 aluminum alloy (heat-treated—T3)	0.17	780	113,000
AZ-31B magnesium alloy (annealed)	0.16	450	66,000

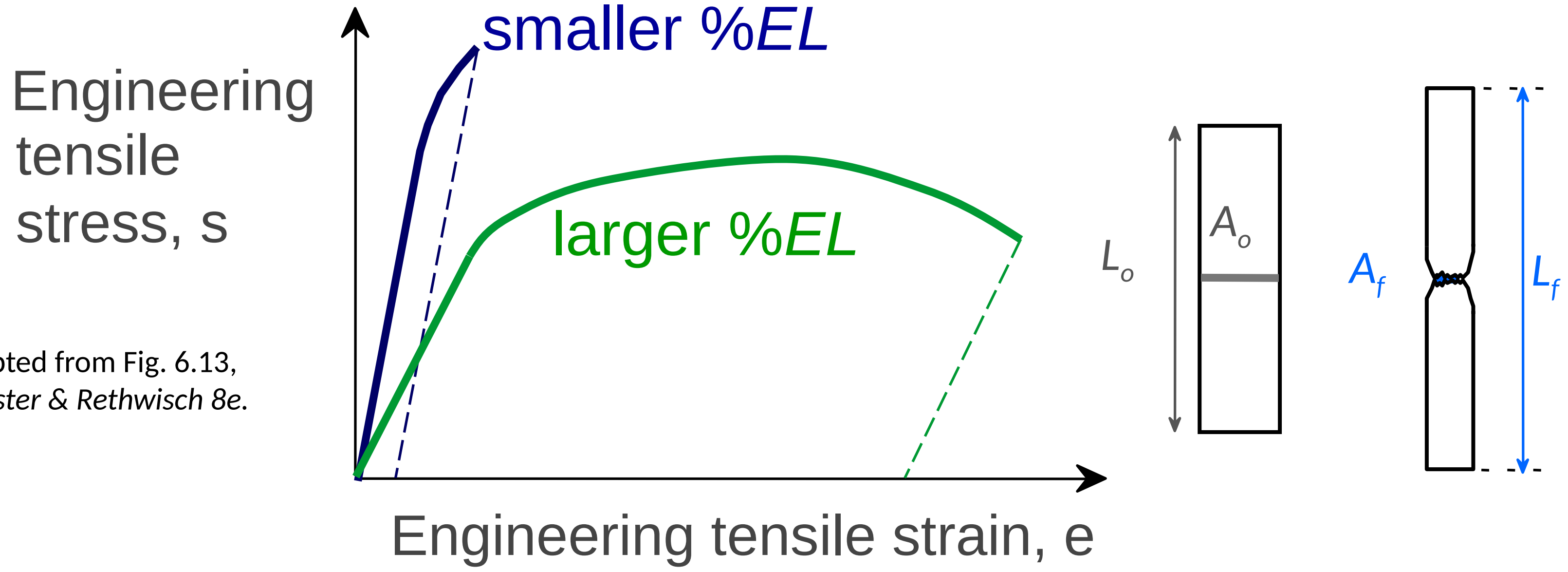
Compute the strain-hardening exponent n in for an alloy in which a true stress of 555 MPa produces a true strain of 0.11; assume a value of 1035 MPa for K.

Ductility

- Plastic tensile strain at failure:

Elongation

$$\% EL = \frac{L_f - L_o}{L_o} \times 100$$



Adapted from Fig. 6.13, *Callister & Rethwisch 8e.*

- Another ductility measure:

$$\% RA = \frac{A_o - A_f}{A_o} \times 100$$

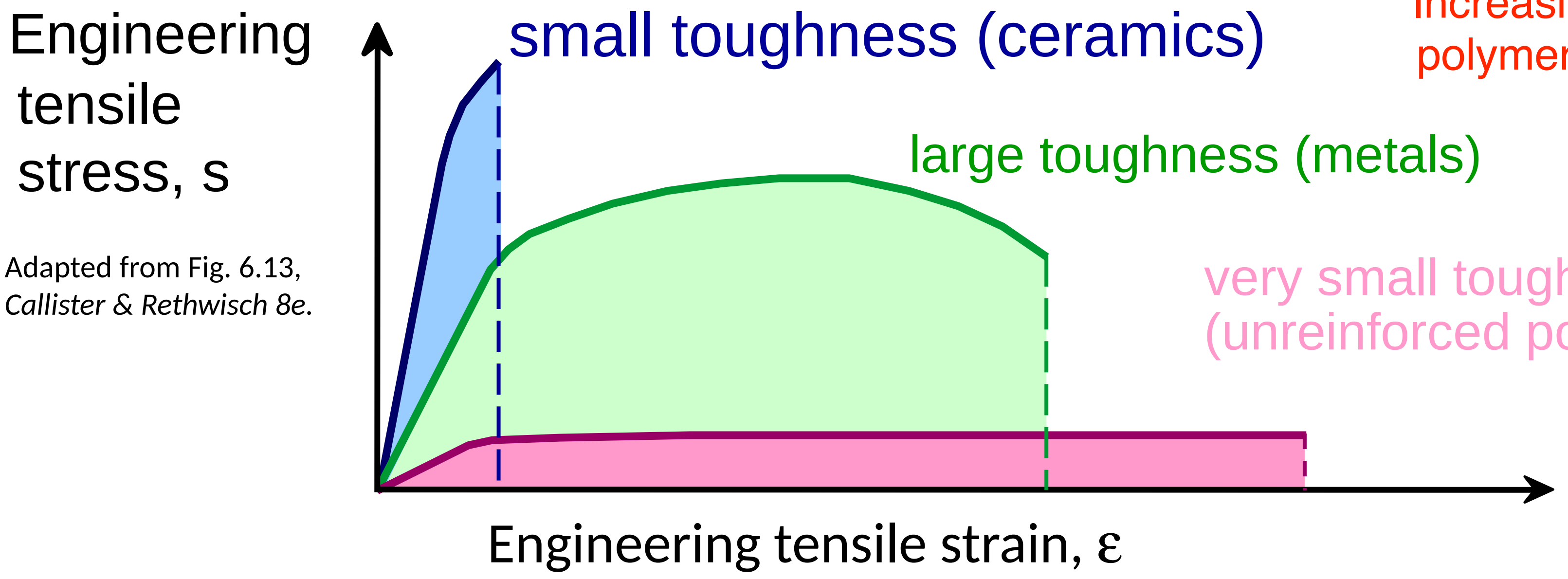
Reduction in Area

A cylindrical specimen of steel having an original diameter of 18.5 mm is tensile-tested to fracture and found to have an engineering fracture strength σ_f of 530 MPa.

If its cross-sectional diameter at fracture is 16.7 mm, determine
(a) The ductility in terms of percentage reduction in area
(b) The true stress at fracture

Toughness

- Energy to break a unit volume of material/ or the ability of a material to absorb energy and plastically deform up-to fracturing
- Approximate by the area under the stress-strain curve.



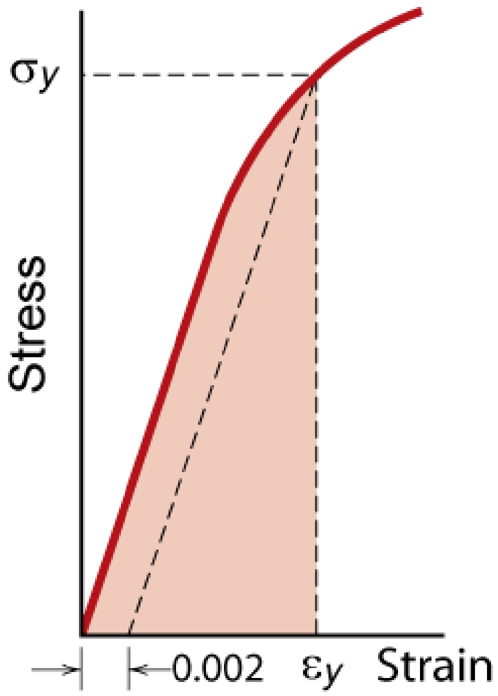
Adapted from Fig. 6.13, *Callister & Rethwisch 8e.*

Increasing order of toughness:
polymers < ceramics < metals

Brittle fracture: elastic energy
Ductile fracture: elastic + plastic energy

Resilience

- Ability of a material to absorb energy when it is *deformed elastically*, and release that energy upon unloading



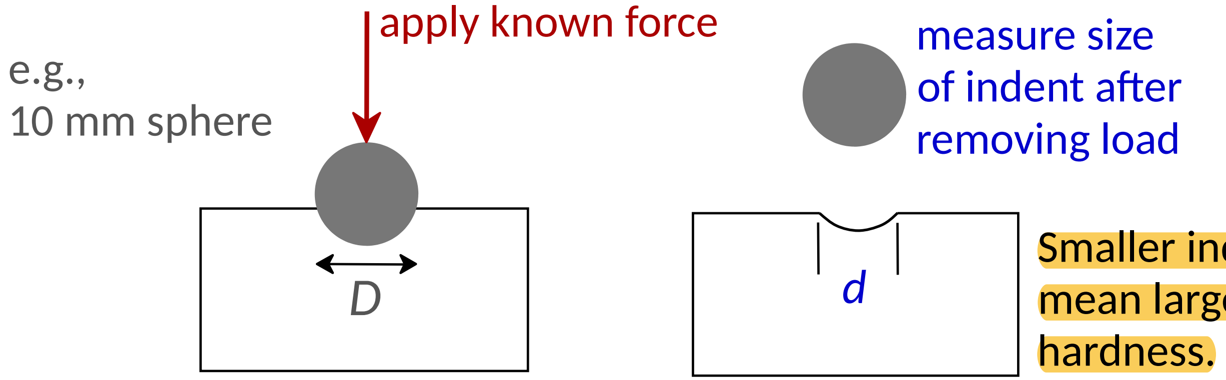
Adapted from Fig. 6.15, *Callister & Rethwisch 8e.*

If we assume a linear stress-strain curve this simplifies to

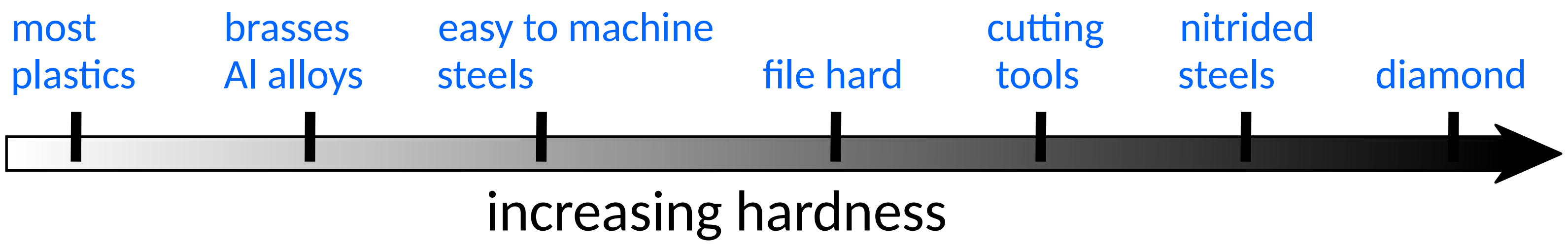
$$\boxed{U_r \cong \frac{1}{2}\sigma_y \varepsilon_y}$$

Hardness

- Resistance to permanently indenting the surface.
- Large hardness means:
  - -- resistance to plastic deformation or cracking in compression.
  - -- better wear properties.



Smaller indents mean larger hardness.



Sections from textbook:

Chapter 6: Sections 6.1-6.9