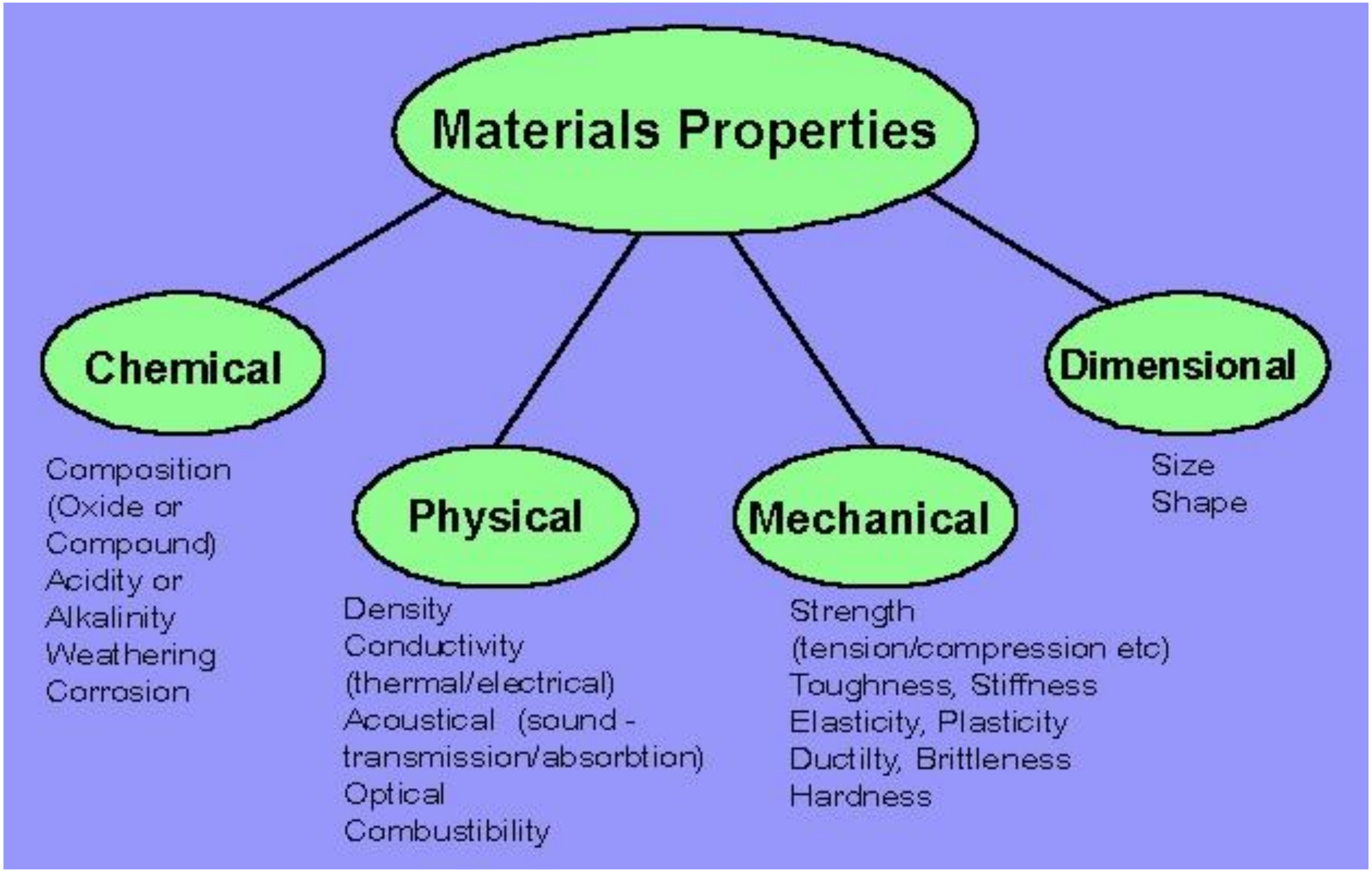
CHARACTERIZATION OF MATERIALS

MECHANICAL PROPERTIES

Among the most important properties for the application of materials in medicine and dentistry are the "*mechanical properties*".



Materials Properties

Chemical

Composition
(Oxide or
Compound)
Acidity or
Alkalinity
Weathering
Corrosion

Physical

Density
Conductivity
(thermal/electrical)
Acoustical (sound - transmission/absorbtion)
Optical
Combustibility

Mechanical

Strength
(tension/compression etc)
Toughness, Stiffness
Elasticity, Plasticity
Ductilty, Brittleness
Hardness

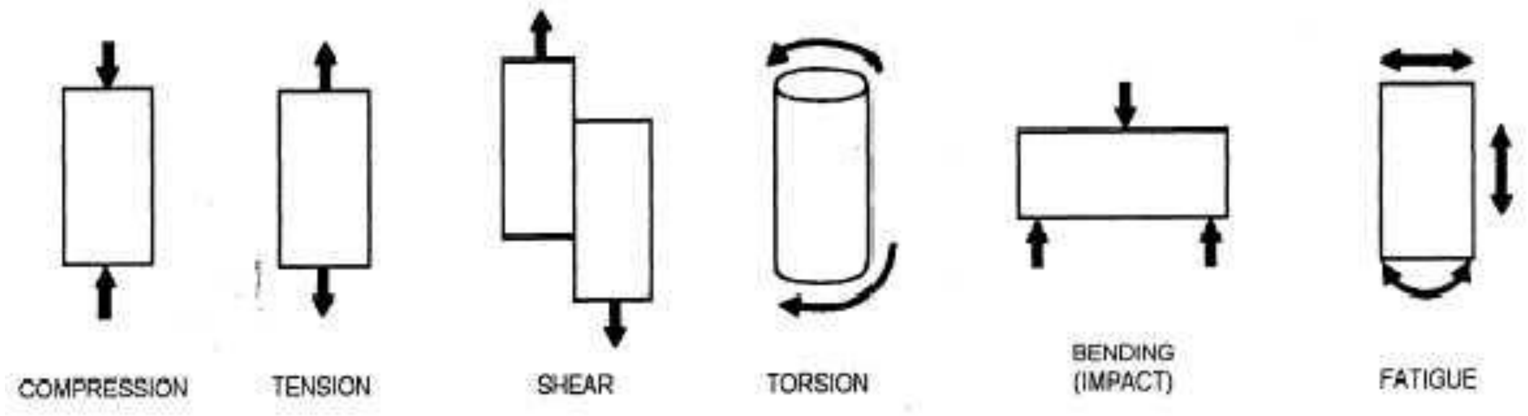
Dimensional

Size
Shape

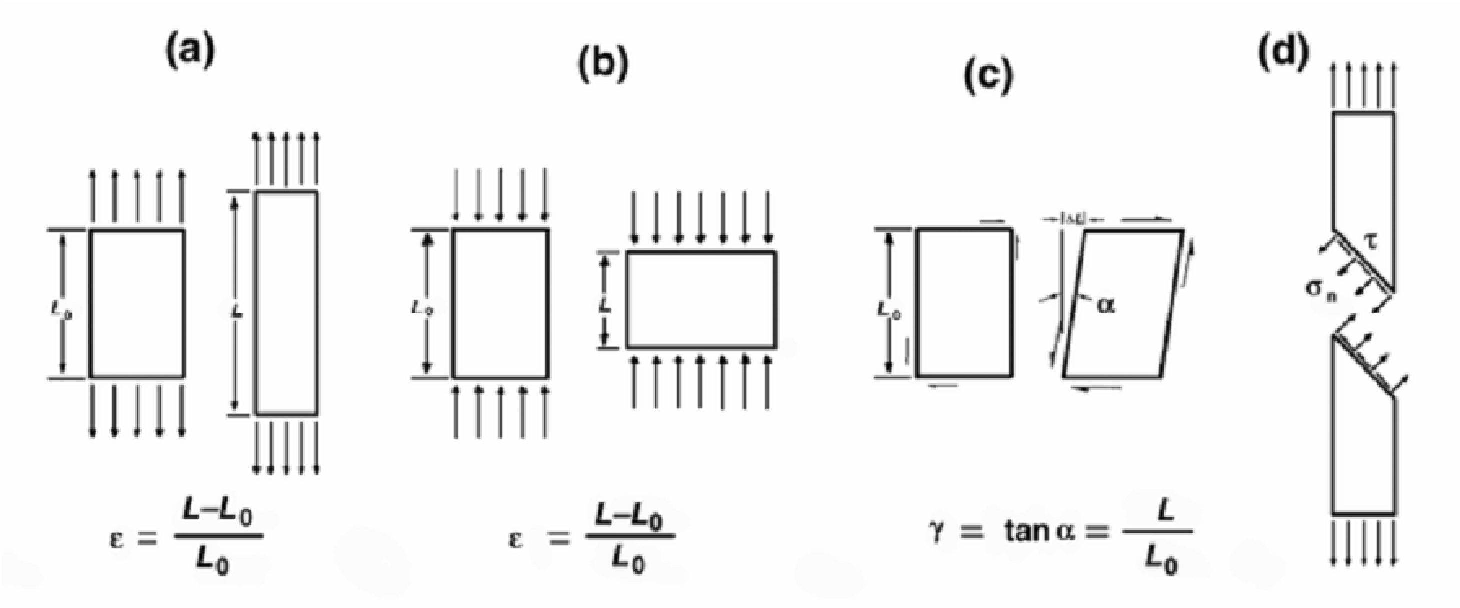
1. Stress–Strain Behavior

$$\text{Stress } (\sigma) = \frac{\text{force}}{\text{cross-sectional area}} \left[\frac{\text{N}}{\text{m}^2}\right] \text{ or } \left[\frac{\text{lbf}}{\text{in}^2}\right].$$

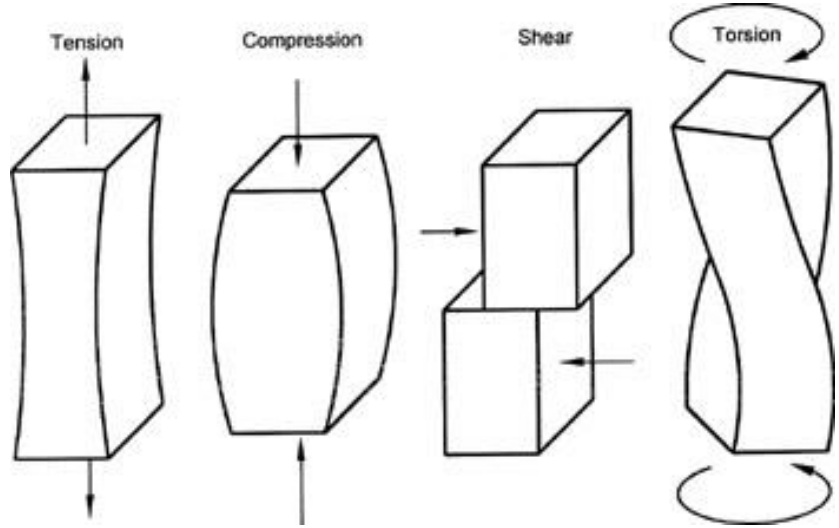
$$\text{Strain } (\varepsilon) = \frac{\text{deformed length} - \text{original length}}{\text{original length}} \left[\frac{\text{m}}{\text{m}}\right] \text{ or } \left[\frac{\text{in}}{\text{in}}\right].$$

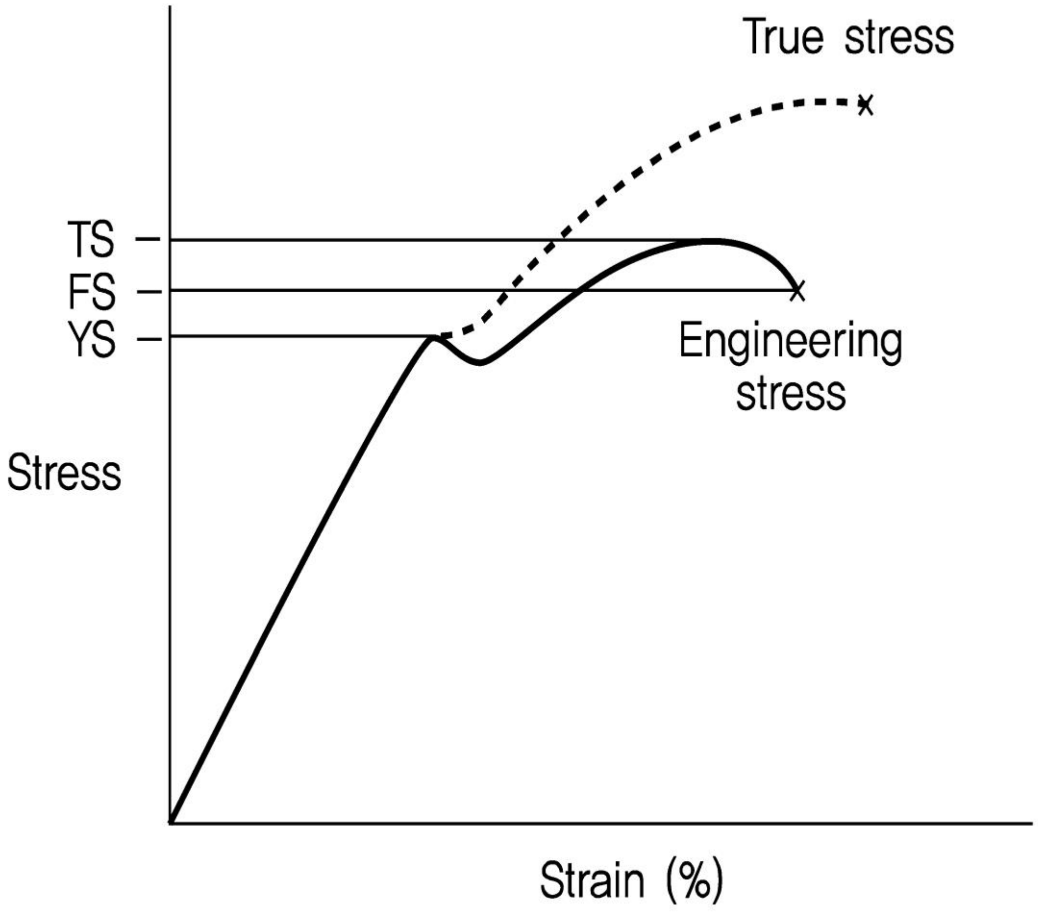


Stress applied to a material



Three different modes of deformation: (a) tension, (b) compression, (c) shear, and (d) shear in tension. The shear stresses can be produced by tension or compression as in (d).

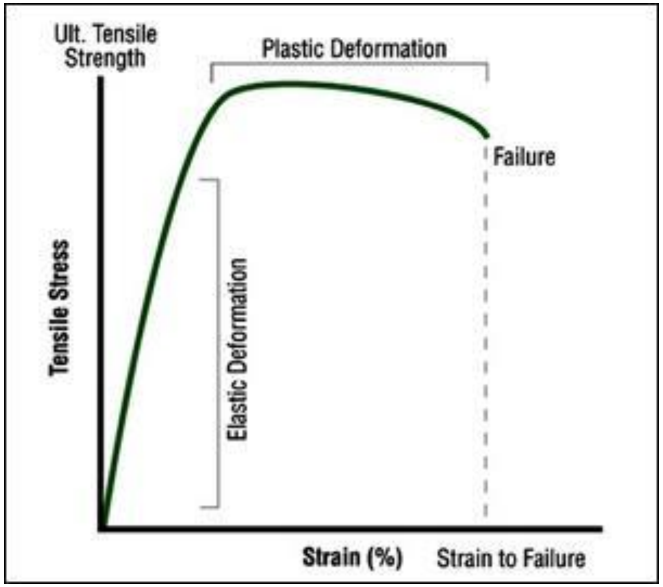




Stress–strain behavior of an idealized material

In the elastic region:

- **the strain ε increases in direct proportion to the applied stress σ (Hooke's law):**



$$\sigma = E\varepsilon : \text{stress} = (\text{initial slope}) \times (\text{strain})$$

The slope (E) or proportionality constant of the tensile/compressive stress–strain curve is called *Young's modulus* or the *modulus of elasticity*

Young's modulus (the modulus of elasticity)

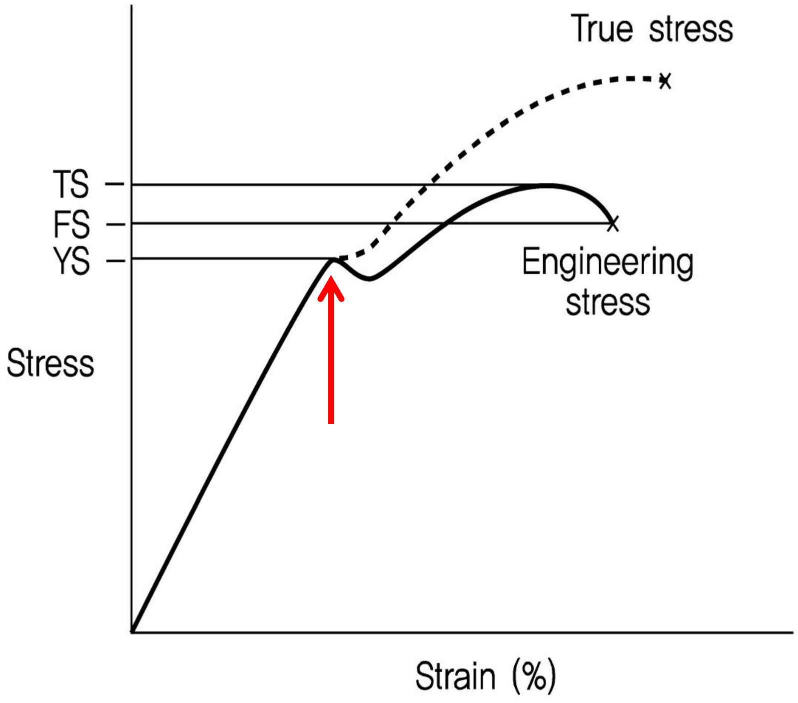
- It is the value of the increment of stress over the increment of strain.
- The stiffer a material is, the higher the value of E : more difficult to deform.
- Similar analysis can be performed for deformation by shear, in which the shear modulus (G) is defined as the initial slope of the curve of shear stress versus shear strain.
- The unit for the modulus is the same as that of stress since strain is dimensionless.
- The shear modulus of an isotropic material is related to its Young's modulus by

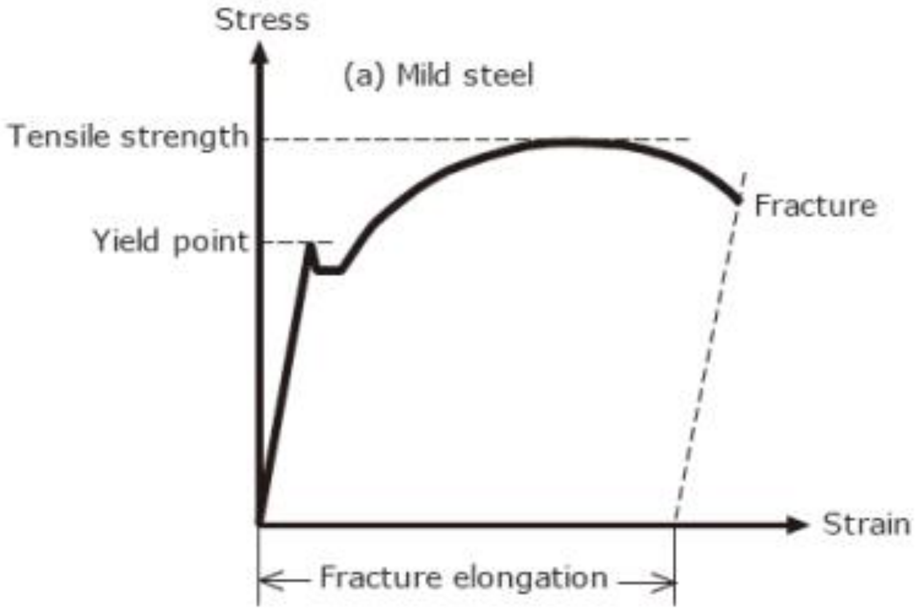
$$E= 2G(1+v)$$

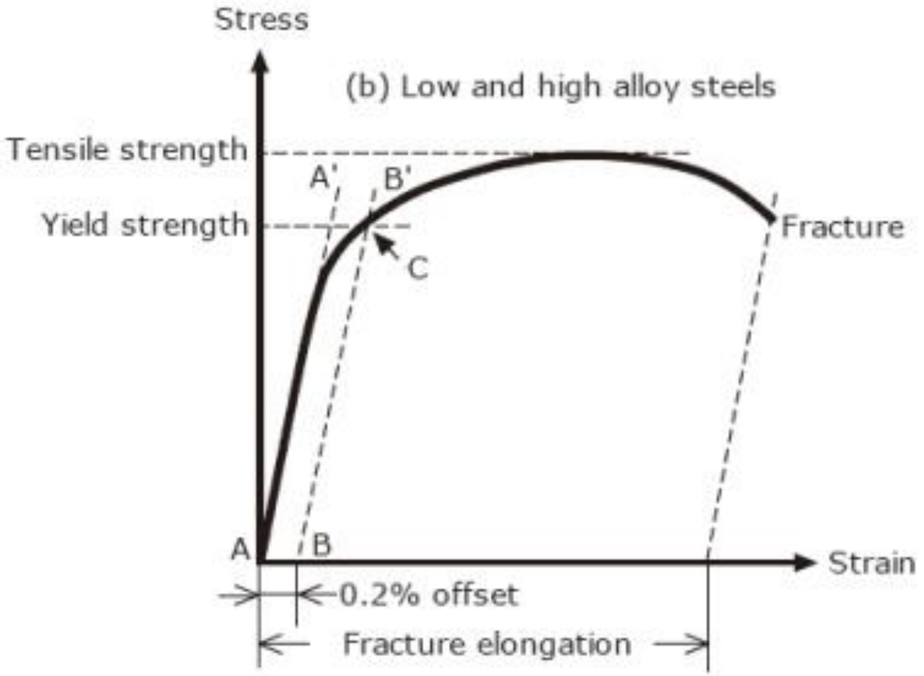
v is the Poisson's ratio of the material

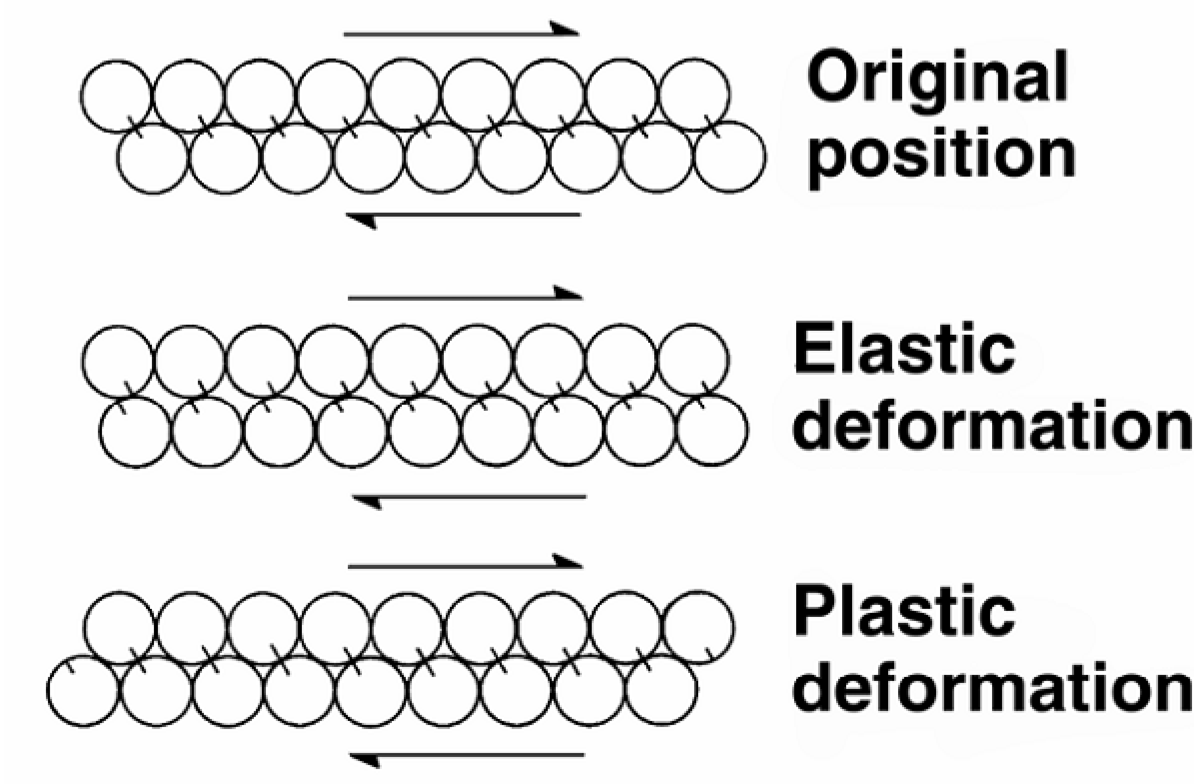
In the plastic region

- strain changes are no longer proportional to the applied stress.
- when the applied stress is removed, the material will not return to its original shape but will be permanently deformed →a plastic deformation
  (yield point; 항복점)




Stress
(a) Mild steel
Tensile strength
Yield point
Fracture
Strain
Fracture elongation


Stress
(b) Low and high alloy steels
Tensile strength
A'
B'
Yield strength
C
Fracture
A
B
Strain
0.2% offset
Fracture elongation



Schematic diagrams of a two-dimensional atomic model after elastic and plastic deformation.

- **The peak stress →**
  tensile or ultimate tensile strength (TS)
- **The stress where failure occurs**
  → the failure or fracture strength (FS)

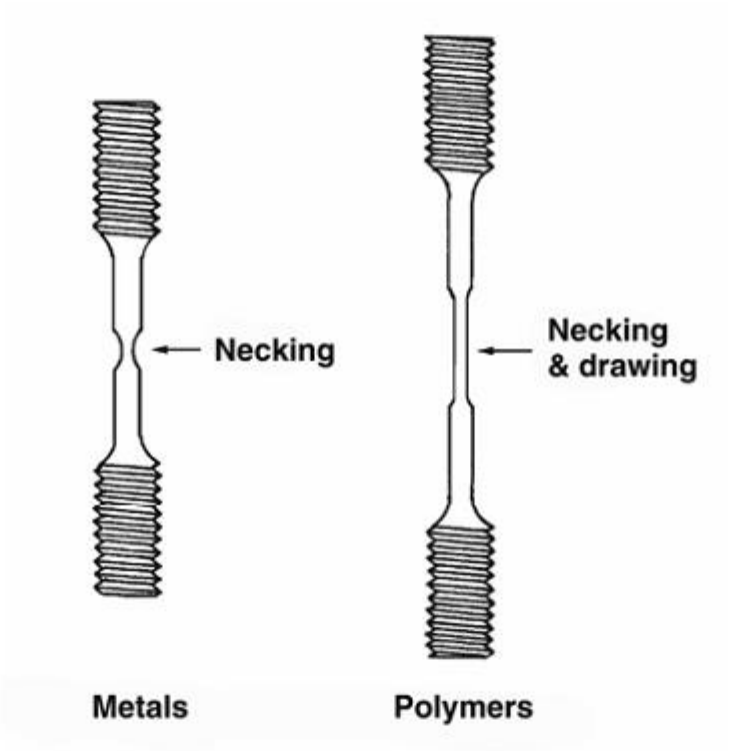
Sometimes it is difficult to decipher the yield point since the deviation from linear behavior may be obscured by noise in the data. Therefore, an offset (usually 0.2 to 1.0%) yield point is used in lieu of the original yield point.

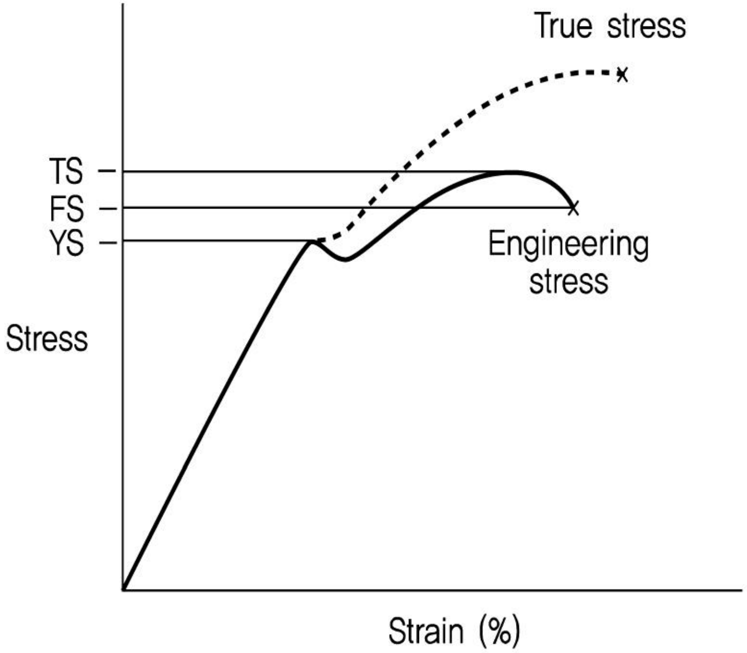
engineering stress–strain curves

⇩

assuming a constant cross-sectional area over which the load is acting from the initial loading until final rupture.

Why engineering stress–strain curves?



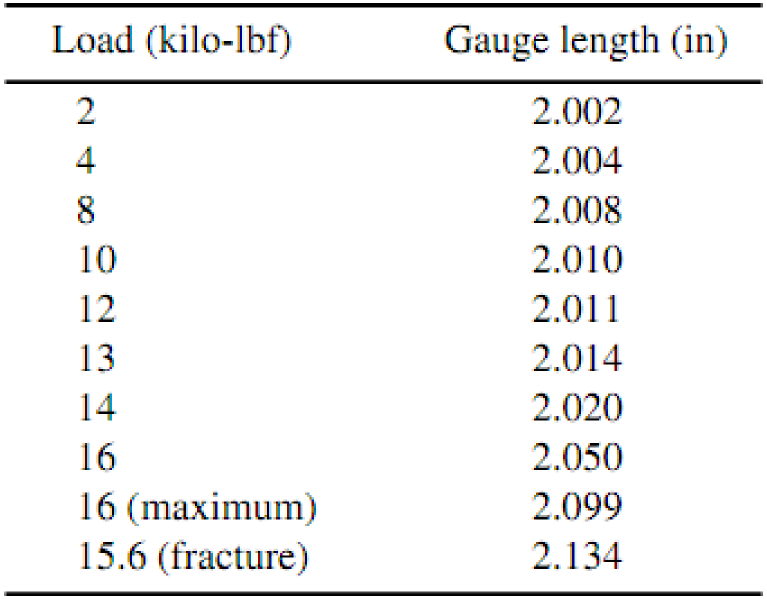


Deformation characteristics of metals and plastics under stress. Note that metals rupture without further elongation after necking occurs; by contrast, in plastics the necked region undergoes further deformation, called drawing.

Example

The following data were obtained for an aluminum alloy. A standard tensile test specimen with a 2-inch gauge length and 0.505 inch diameter was used:

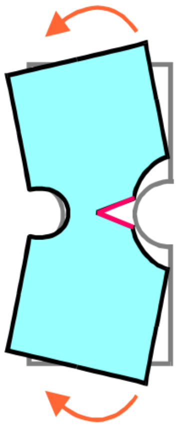
- **a. Plot the engineering stress–strain curve.**
- **b. Determine the Young's modulus, yield strength (0.2% offset), and tensile strength.**
- **c. Determine the engineering and true fracture strength. The diameter of the broken pieces was 0.4 in.**



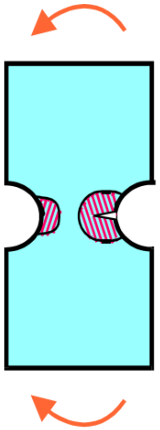
Load (kilo-lbf)	Gauge length (in)
2	2.002
4	2.004
8	2.008
10	2.010
12	2.011
13	2.014
14	2.020
16	2.050
16 (maximum)	2.099
15.6 (fracture)	2.134

2. Mechanical Failure

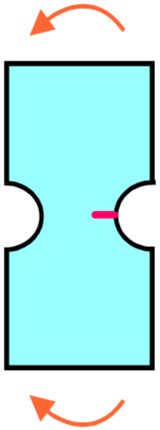
- ✓ **Static failure**
- ✓ **Dynamic fatigue failure**
- **Friction and wear failure**



Static failure
(large global
deformation and
large plastic strain)



Low cycle fatigue
(small local plastic
strains)

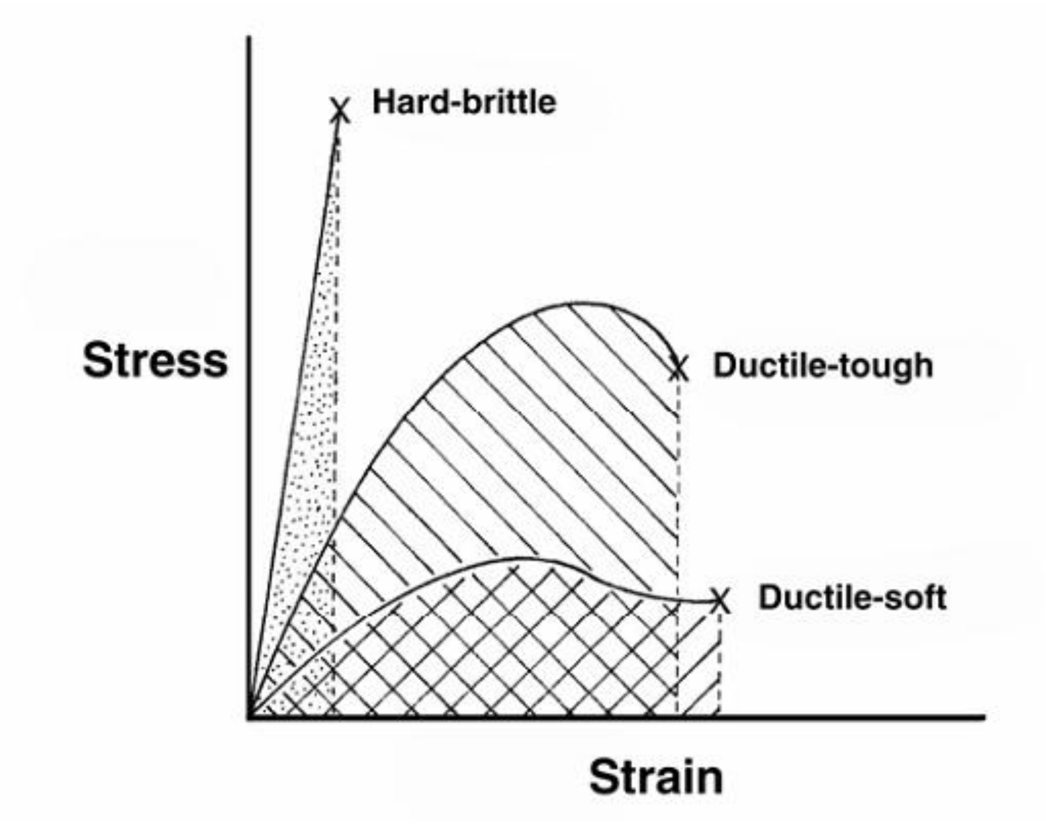


High cycle fatigue
(small local elastic
strains)

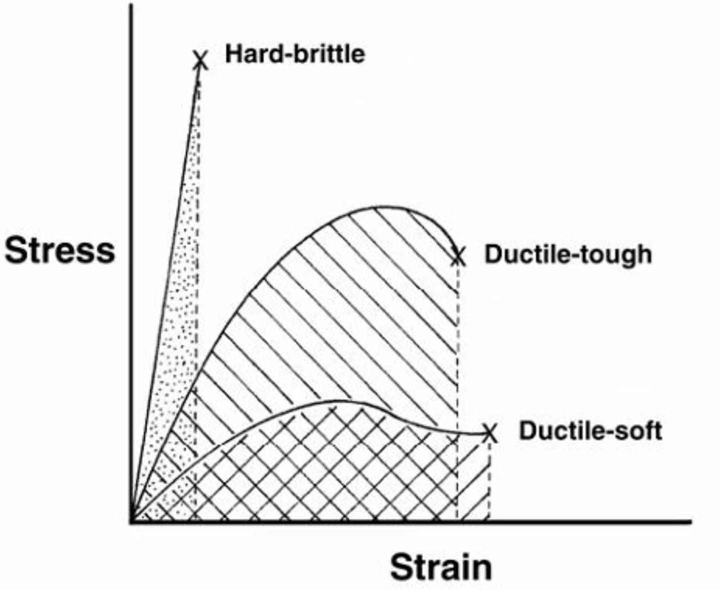
Static failure

- Mechanical failure usually occurs by fracture.
- The fracture of a material can be characterized by the amount of energy per unit volume required to produce the failure.
- The quantity is called **toughness** and can be expressed in terms of stress and strain:

$$\text{toughness} = \int_{\varepsilon_o}^{\varepsilon_f} \sigma \, d\varepsilon = \int_{l_0}^{l_f} \sigma \frac{dl}{l}.$$



Stress–strain curves of different types of materials. The areas underneath the curves are the measure of toughness.



Ductile-tough material

- **A material that can withstand high stresses and can undergo considerable plastic deformation**

Hard-brittle material

- **resists high stresses but has no capacity for deformation**

Ductile-soft or plastic material

- **one with a high capacity for deformation but can only withstand relatively low stresses.**

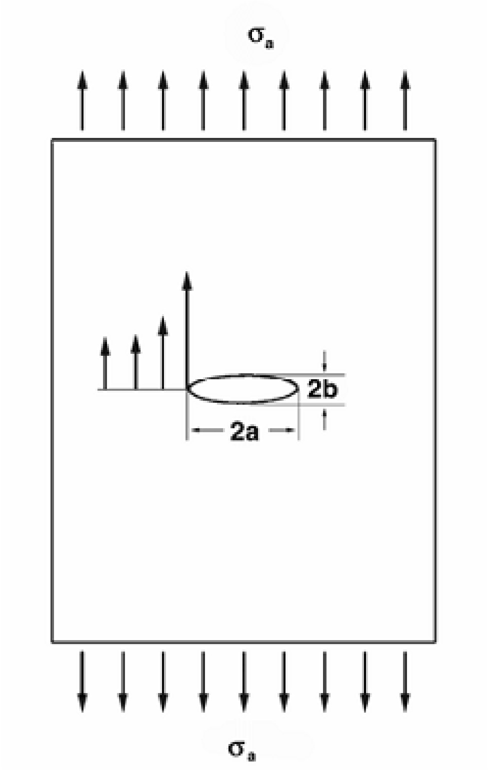
충격 특성

금속생체재료가 충격하중을 받을 경우 소성변형 (plastic deformation) 을 일으키지 않고 파괴되는 성질을 취성 (brittle)이라고 하고, 그 반대로 소성변형을 일으키면서 변형되는 성질을 연성 (ductile)이라 한다

재료의 변형에 소모된 에너지를 인성 (toughness)이라 한다

인성은 재료가 파괴될 때까지 에너지를 흡수하는 능력으로 정의되고, 일반적으로 응력-변형률 곡선에서 곡선과 가로축 사이의 면적으로 간주

- **The stress on a brittle material is not uniformly distributed over the entire cross-sectional area if a crack or flaw is present, as shown in Figure**
- **If the crack is a narrow elliptic hole in a specimen subjected to a tensile stress, the maximum stress (σ_{max}) acting at the ends of the hole is given by**



$$\sigma_{max} = \sigma_{app}\left(1 + \frac{2a}{b}\right),$$

$$\frac{\sigma_{max}}{\sigma_{app}} = \left(1 + \frac{2a}{b}\right),$$

where the ratio $\sigma_{max}/\sigma_{app}$ is called the stress concentration factor (scf),

- if ratio a/b is high (i.e., a sharp crack)
  → stress concentration factor (scf) can be substantial
- If the crack tip has a radius of curvature r $(= b^2/a)$,

$$\sigma_{max} = \sigma_{app}\left[1 + 2\left(\frac{a}{r}\right)^{1/2}\right]$$

Since $a \gg r$ for a crack,

$$\sigma_{max} \cong 2\sigma_{app}\left(\frac{a}{r}\right)^{1/2}$$

Griffith proposal (1920): an energy approach to fracture

$$\sigma \times \varepsilon = \pi a^2 \sigma \left(\frac{\sigma}{E} \right) = \frac{\pi (a\sigma)^2}{E}.$$

Observe that the elastic energy for a brittle material is twice the area under the stress–strain curve. The elastic energy is used to create two new surfaces as the crack propagates.

The surface energy, $4\gamma a$ (γ is the surface energy) should be smaller than the elastic energy for the crack to grow.

Thus, the incremental changes of both energies for the crack to grow can be written as

$$\frac{d}{da}\left(\frac{\pi (a\sigma)^2}{E} \right) = \frac{d}{da}(4\gamma a).$$

Hence,

$$\sigma = \sigma_f = \sqrt{\frac{2\gamma E}{\pi a}}.$$

Since for a given material E and γ are constants,

$$\sigma_f = \frac{K}{\sqrt{\pi a}}.$$

In this case, *K* has the units of psi√in or MPa√m and is proportional to the energy required for fracture. *K* is also called “fracture toughness”

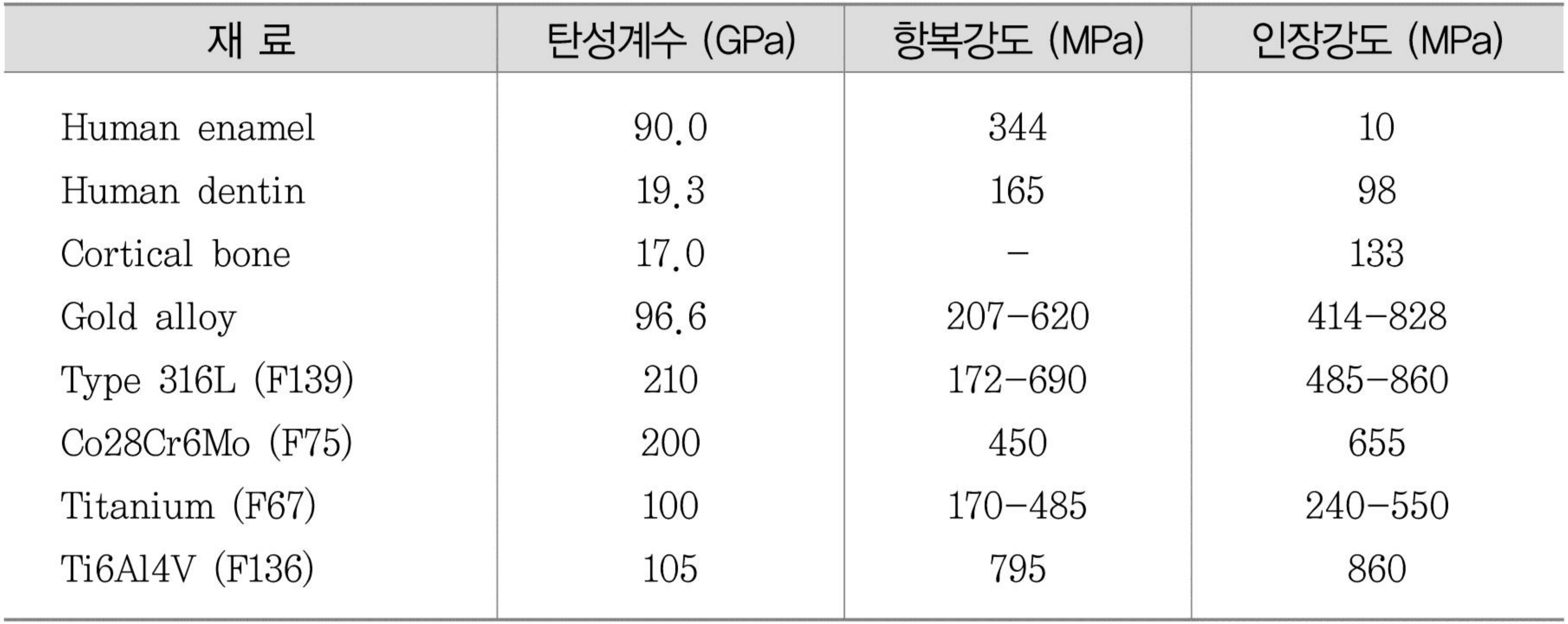
Example

Estimate the size of the surface flaw in a glass whose modulus of elasticity and surface energy are 70 GPa and 800 erg/cm^2, respectively. Assume that the glass breaks at a tensile stress of 100 MPa.

Answer

$$\begin{aligned} a &= \frac{2\gamma E}{\pi\sigma_f^2} \\ &= \frac{2\times 800 \text{ dyne/cm}\times 70 \text{ GPa}}{\pi(100 \text{ MPa})^2} \\ &= \underline{3.6\ \mu\text{m}}. \end{aligned}$$

[Note that if the crack is on the surface its length is *a*; if it is inside the specimen it is 2*a*. Remember that 1 dyne = 10^{-5} N, 1 cm = 10^{-2} m, and 1 erg = 1 dyne cm.]



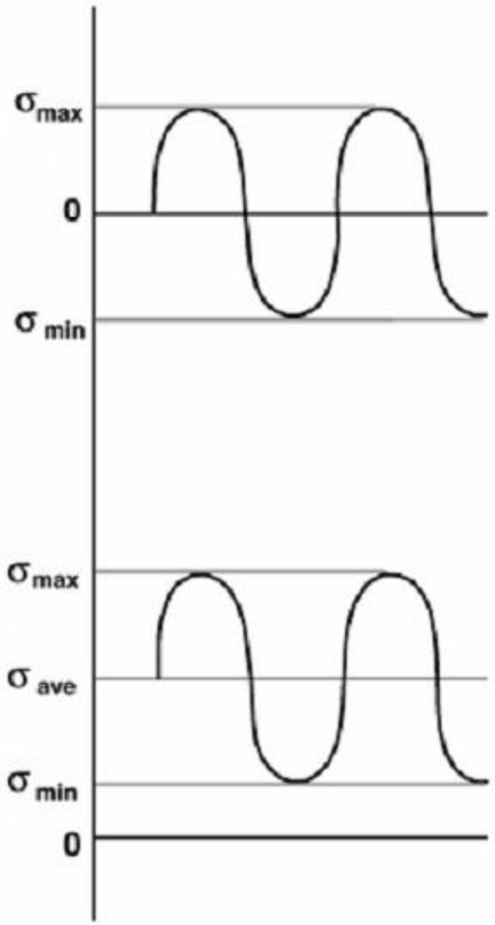
재 료	탄성계수 (GPa)	항복강도 (MPa)	인장강도 (MPa)
Human enamel	90.0	344	10
Human dentin	19.3	165	98
Cortical bone	17.0	–	133
Gold alloy	96.6	207–620	414–828
Type 316L (F139)	210	172–690	485–860
Co28Cr6Mo (F75)	200	450	655
Titanium (F67)	100	170–485	240–550
Ti6Al4V (F136)	105	795	860

생체 경조직과 주요 금속재료들의 탄성계수, 항복강도, 인장강도 등을 비교한 표

Dynamic fatigue failure

When a material is subjected to a constant or a repeated load below the fracture stress,
→it can fail after some time.

This is called static or dynamic (cyclic) fatigue respectively.

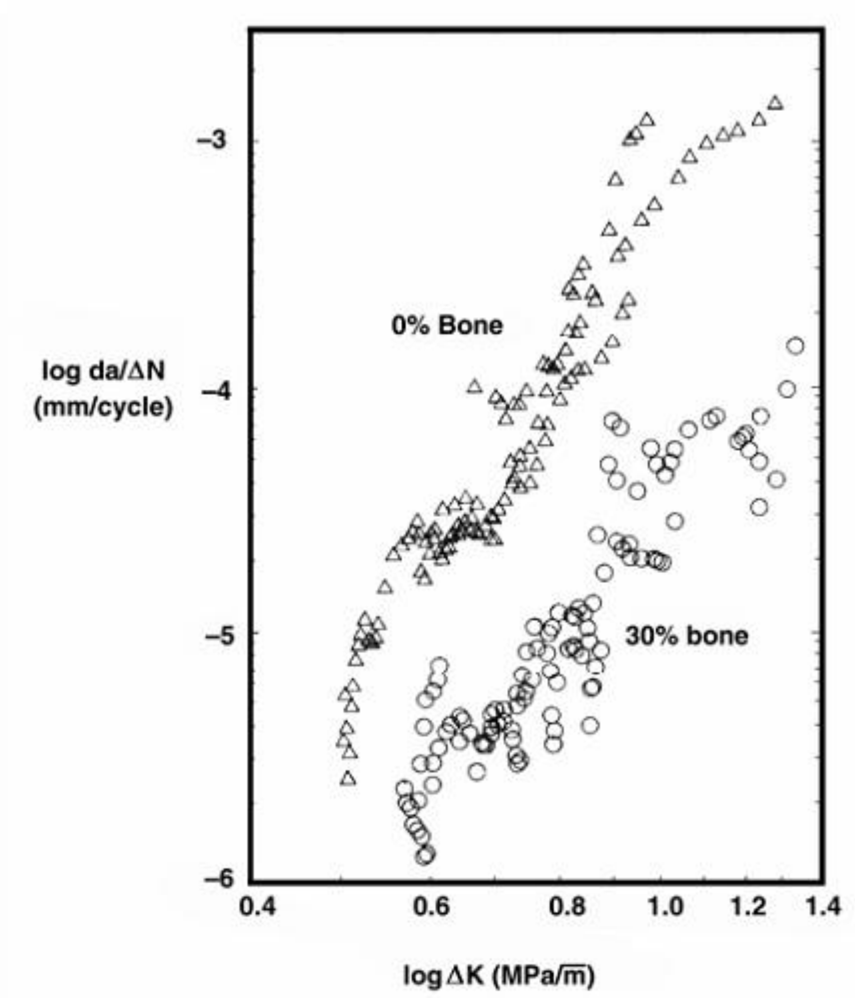


cyclic stresses

→ initiate microcracks at centers of stress concentration within the material or on the surface
→ resulting in the growth and propagation of cracks
→ leading to failure.

Figure Cyclic stresses. σ_{min} and σ_{max} are the maximum and minimum values of the cyclic stresses. The range of stresses $\Delta\sigma = \sigma_{min} - \sigma_{max}$ and average stress $\sigma_{ave} = (\sigma_{max} + \sigma_{min})/2$. The top curve is fluctuating, and the bottom curve is for reversed cyclic loading.

the crack propagation stage



Log da/dN versus log ΔK for polymethylmethacrylate bone cement.

$$\frac{da}{dN} = A(\Delta K)^m$$

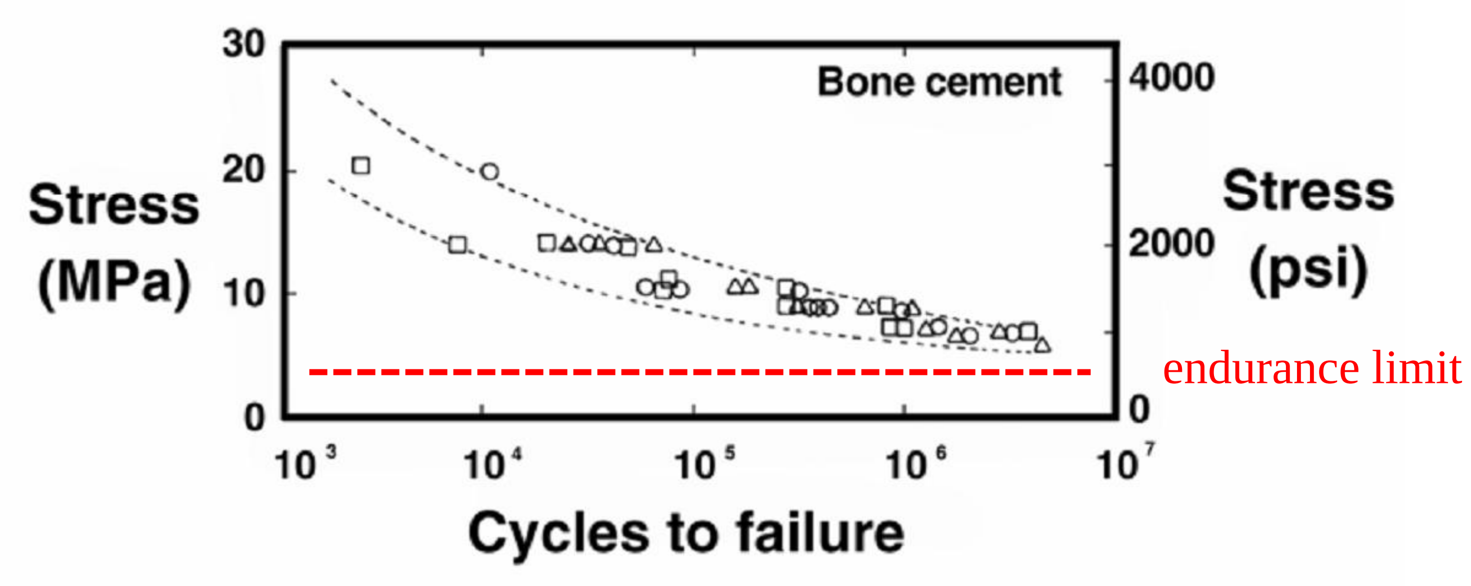
Where:

a; the crack length

N; number of cycles

ΔK; range of stress intensity factor

$$\Delta K = \Delta\sigma \sqrt{\pi a}$$



Stress versus log N (number of cycles) of PMMA bone cement. The Simplex P bone cement test specimens were fabricated at pressures between 5 and 50 psi and tested in air at 22ºC.

cf.

- **The endurance limit is the stress below which the material will not fail in fatigue no matter how many cycles are applied.**
- **Normally 10^7 cycles is considered as a representative limit for normal fatigue failure.**
- **Not all materials exhibit an endurance limit. Since implants are often flexed many times during a patient's life, the fatigue properties of materials are very important in implant design.**

3. Viscoelasticity

- **Viscoelastic materials are those for which the relationship between *stress and strain depends on time*.**
- **In such materials the stiffness will depend on the rate of application of the load.**
- **In addition, mechanical energy is dissipated by conversion to heat in the deformation of viscoelastic materials.**
- **All materials exhibit some viscoelastic response.**
- **Synthetic polymers, wood, and human tissue display significant viscoelastic effects**

Creep

- **Creep is a slow, progressive deformation of a material under constant stress.**
- **Suppose the history of stress *σ* as it depends on time *t* is a step function beginning at time zero:**

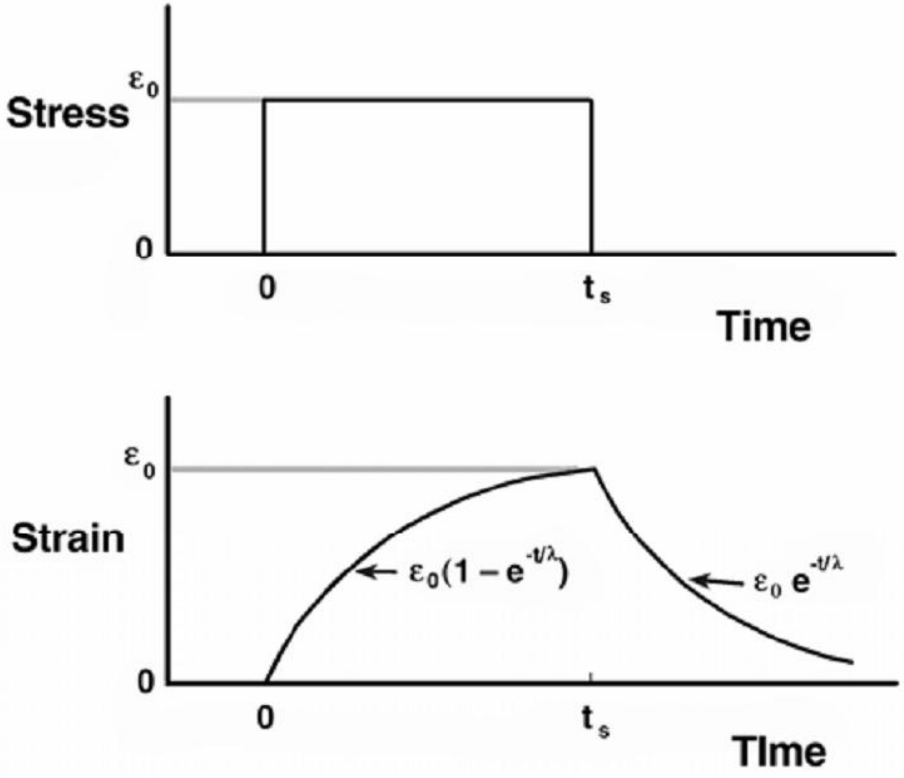
$$\sigma(t) = \sigma_0 H(t),$$

where *H(t)* is the unit Heaviside step function defined as zero for *t* less than zero

- **The strain ε*(t)* will increase**
- **The ratio**

$$J(t) = \frac{\varepsilon(t)}{\sigma_0}$$

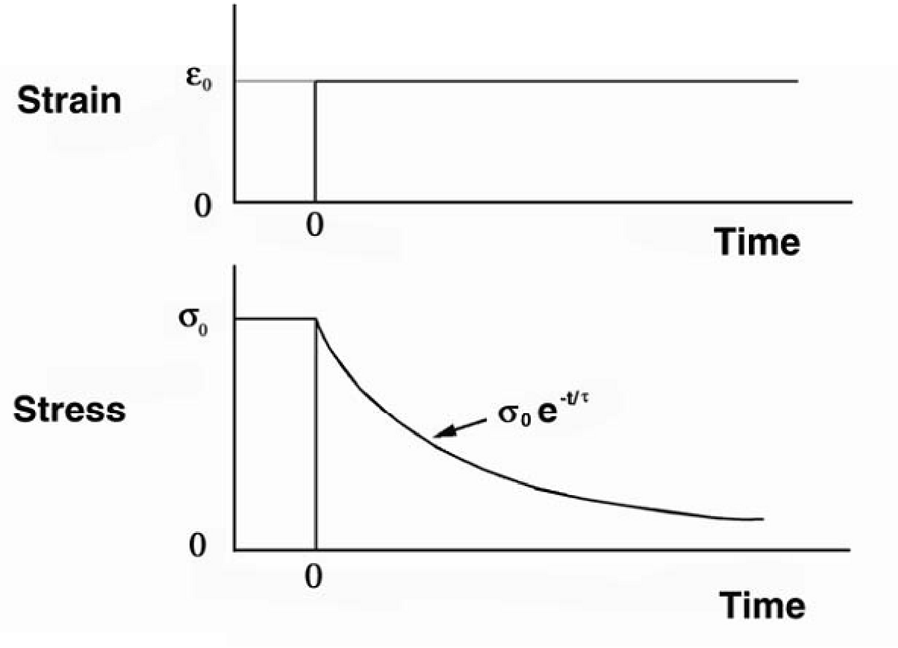
is called the creep compliance.



Creep and creep recovery of an idealized viscoelastic material.

Stress relaxation

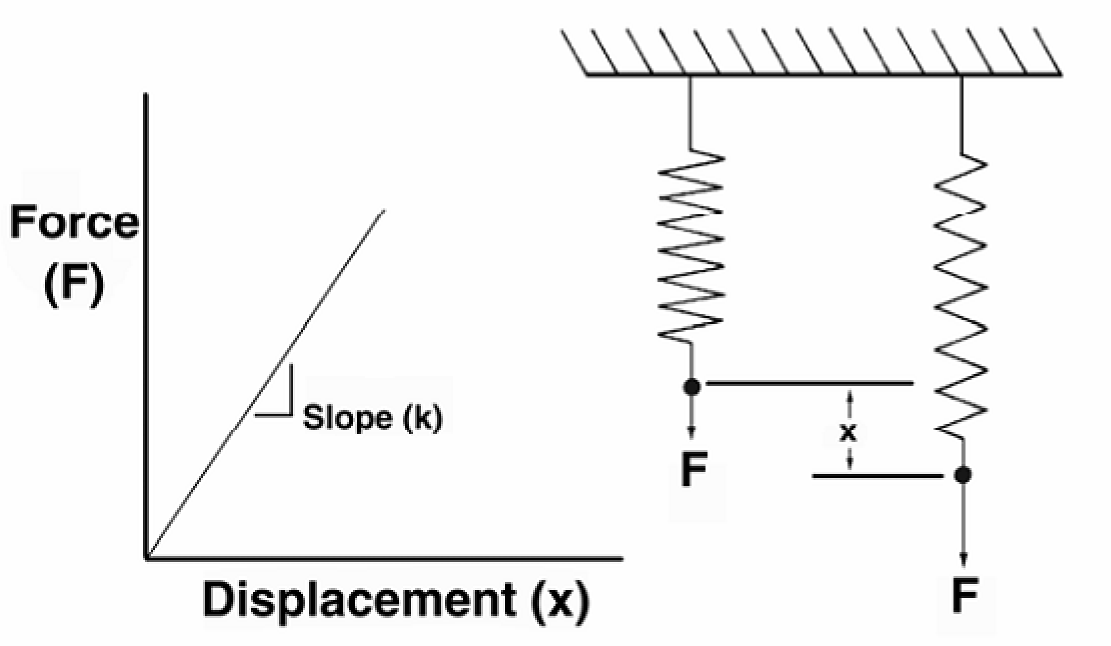
- Stress relaxation is the gradual decrease of stress when the material is held at constant extension.



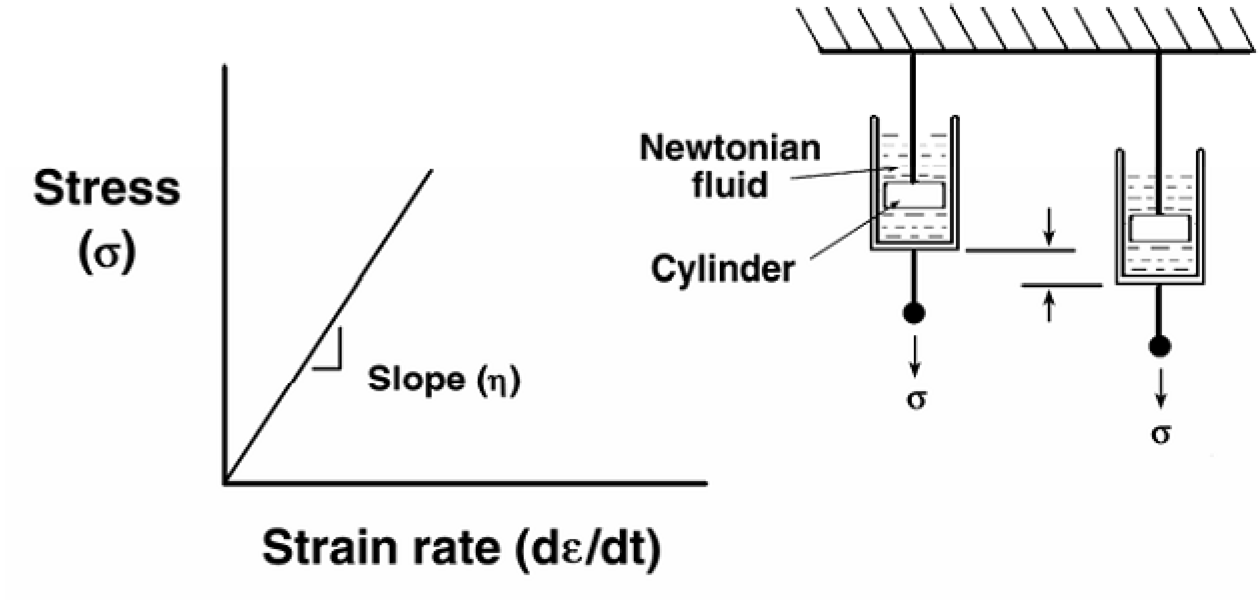
$$E(t) = \frac{\sigma(t)}{\varepsilon_0}$$

relaxation modulus.

Mechanical models

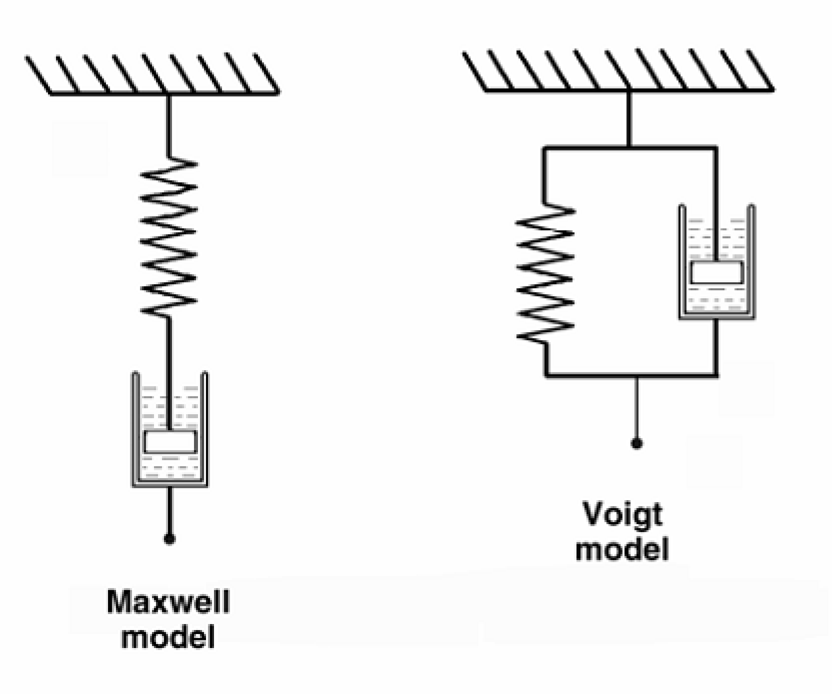


Force versus displacement of a spring.



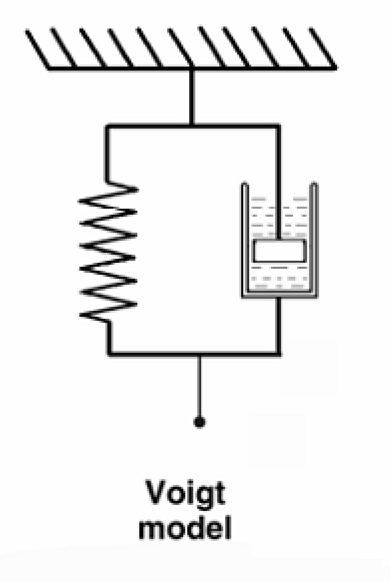
Stress-versus-strain rate of a dashpot.

Mechanical models



Two-element viscoelastic models.

• Voigt model (creep recovery)



$$\sigma = E\varepsilon \qquad \varepsilon_t = \varepsilon_s = \varepsilon_d = \varepsilon$$

$$\sigma = \eta \frac{d\varepsilon}{dt} \qquad \sigma_t = \sigma_s + \sigma_d = \sigma$$

$$\sigma = E\varepsilon + \eta \frac{d\varepsilon}{dt}$$

If stress is removed, then

$$\sigma = E\varepsilon + \eta \frac{d\varepsilon}{dt} = 0$$

$$\varepsilon_{rec} = \varepsilon_0 \exp(-E \frac{t}{\eta})$$

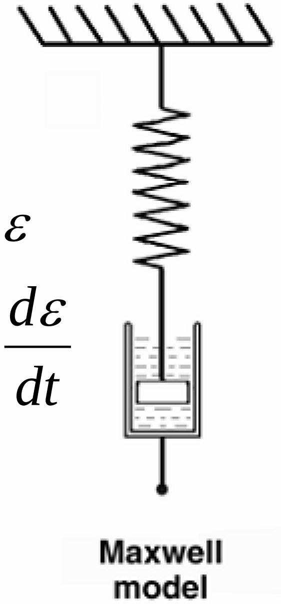
$$\varepsilon(t) = \varepsilon_0 \left[1 - \exp(-\frac{t}{\lambda}) \right]$$

The constant η/E is termed the retardation time **λ** for this *creep recovery* process

- **Maxwell model (stress relaxation)**

$$\sigma = E\varepsilon$$

$$\sigma = \eta \frac{d\varepsilon}{dt}$$



$$\varepsilon_t = \varepsilon_s + \varepsilon_d$$

$$\frac{d\varepsilon_t}{dt} = \frac{d\varepsilon_s}{dt} + \frac{d\varepsilon_d}{dt}$$

$$\frac{d\sigma_s}{dt} = E\,\frac{d\varepsilon_s}{dt}$$

$$\frac{d\varepsilon_t}{dt} = (\frac{1}{E})\frac{d\sigma_s}{dt} + \frac{\sigma_d}{\eta}$$

$$\frac{d\varepsilon}{dt} = (\frac{1}{E})\frac{d\sigma}{dt} + \frac{\sigma}{\eta}$$

for stress relaxation

$$\frac{d\varepsilon}{dt} = 0$$

$$0 = (\frac{1}{E})\frac{d\sigma}{dt} + \frac{\sigma}{\eta}$$

$$\frac{d\sigma}{\sigma} = -E\,\frac{dt}{\eta}$$

$$\frac{\sigma}{\sigma_0} = \exp(-E\,\frac{t}{\eta})$$

$$\sigma = \sigma_0 \exp(-t/\tau)$$

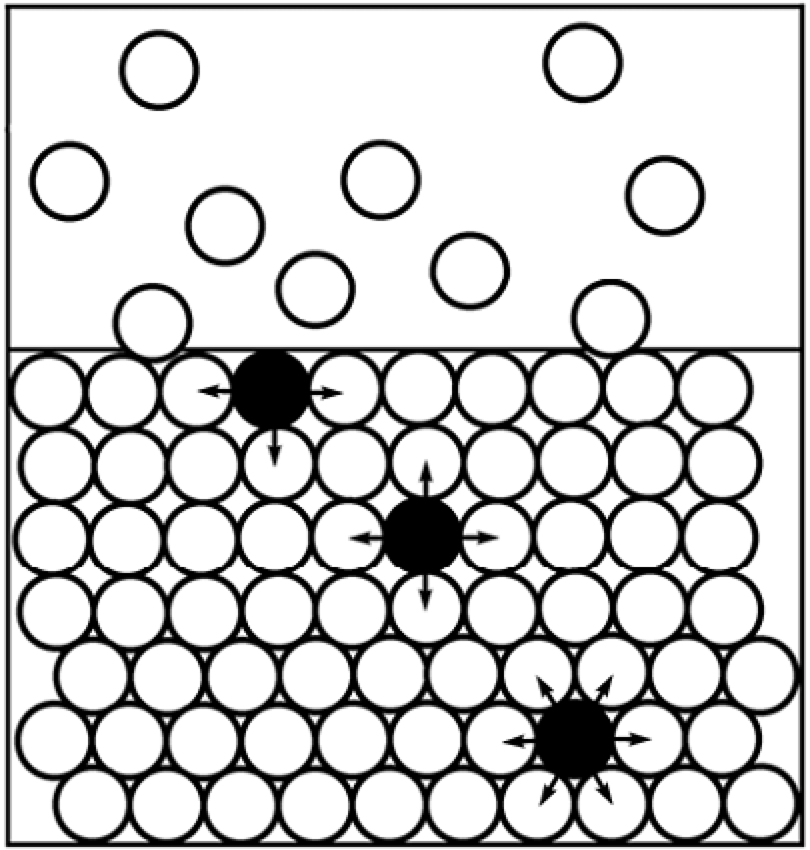
Constant η/E has dimension of time and is defined as the relaxation time **τ**

SURFACE PROPERTIES

- **The surface property is directly related to the bulk property since the surface is the discontinuous boundary between different phases.**

- **If ice is being melted, then there are two surfaces created between three phases: liquid (water), gas (air and water vapor), and solid (ice).**

- **Surface properties are important since all implants interface with the tissues at their surfaces.**



Two-dimensional representation of a surface. Surface molecules are not subject to balanced forces from surrounding atoms in the solid, and are therefore more reactive.

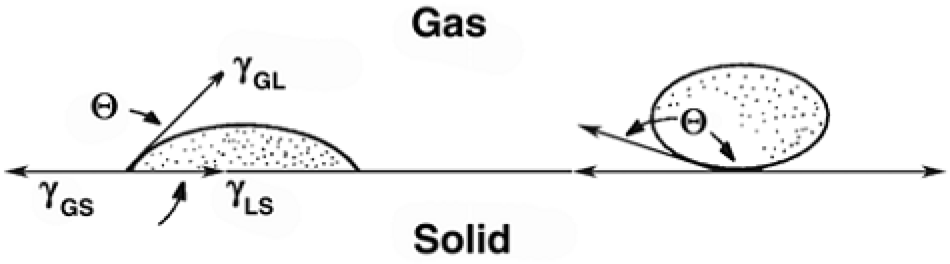
Surface tension

- develops near the phase boundaries since the equilibrium bonding arrangements are disrupted, leading to an excess energy that will minimize the surface area
- Other means of minimizing the surface energy is to attract foreign materials (adsorption) and bonding with adsorbent (chemisorption)

The surface free energy (dG) can be expressed a

$$dG = dw - \gamma dA$$

where w is work done on the surface area change dA, and γ is the surface energy of the material.



Wetting and non-wetting of a liquid on the flat surface of a solid.
Note the contact angle.

If a liquid is dropped on a solid surface, then the liquid droplet will spread or make a spherical globule

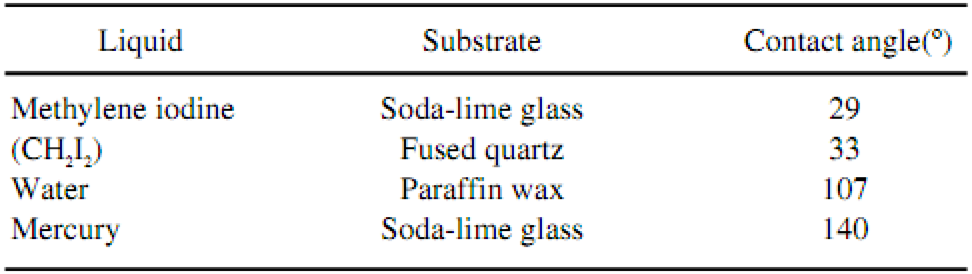
At equilibrium

$$\gamma_{GS} - \gamma_{LS} - \gamma_{GL}\cos\theta = 0, \qquad \cos\theta = \frac{\gamma_{GS} - \gamma_{LS}}{\gamma_{GL}},$$

where θ is called the contact angle

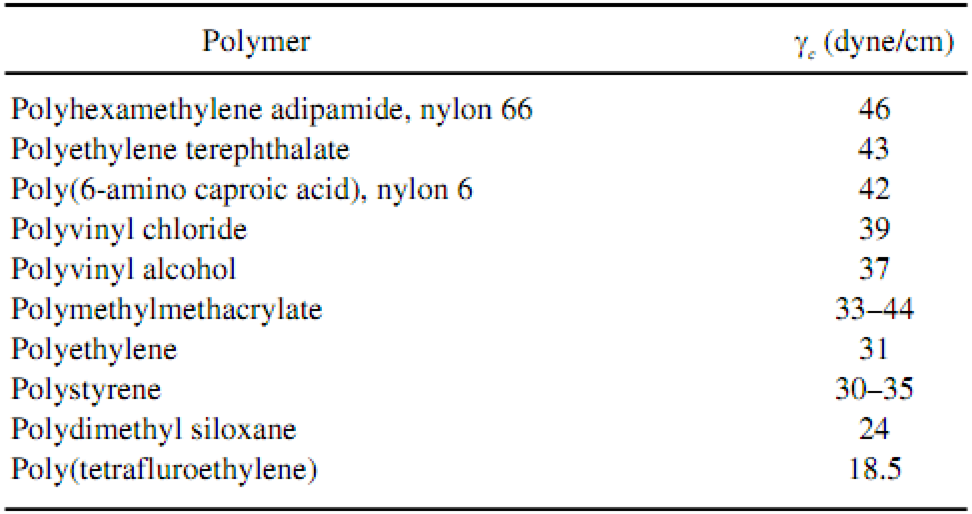
$$\theta = 0 \quad \text{(complete wetting)},$$
$$0 < \theta < 90^\circ \quad \text{(partial wetting)},$$
$$\theta > 90^\circ \quad \text{(non-wetting)}.$$

Contact Angle Values



Liquid	Substrate	Contact angle(°)
Methylene iodine	Soda-lime glass	29
(CH_2I_2)	Fused quartz	33
Water	Paraffin wax	107
Mercury	Soda-lime glass	140

Critical Surface Tension of Polymers



Polymer	γ_c (dyne/cm)
Polyhexamethylene adipamide, nylon 66	46
Polyethylene terephthalate	43
Poly(6-amino caproic acid), nylon 6	42
Polyvinyl chloride	39
Polyvinyl alcohol	37
Polymethylmethacrylate	33–44
Polyethylene	31
Polystyrene	30–35
Polydimethyl siloxane	24
Poly(tetrafluroethylene)	18.5