Deformation of solids

(B.Pharm fourth sem) Physical Pharmacy

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- The changes in materials dimensions in response to mechanical forces is called **deformation.**

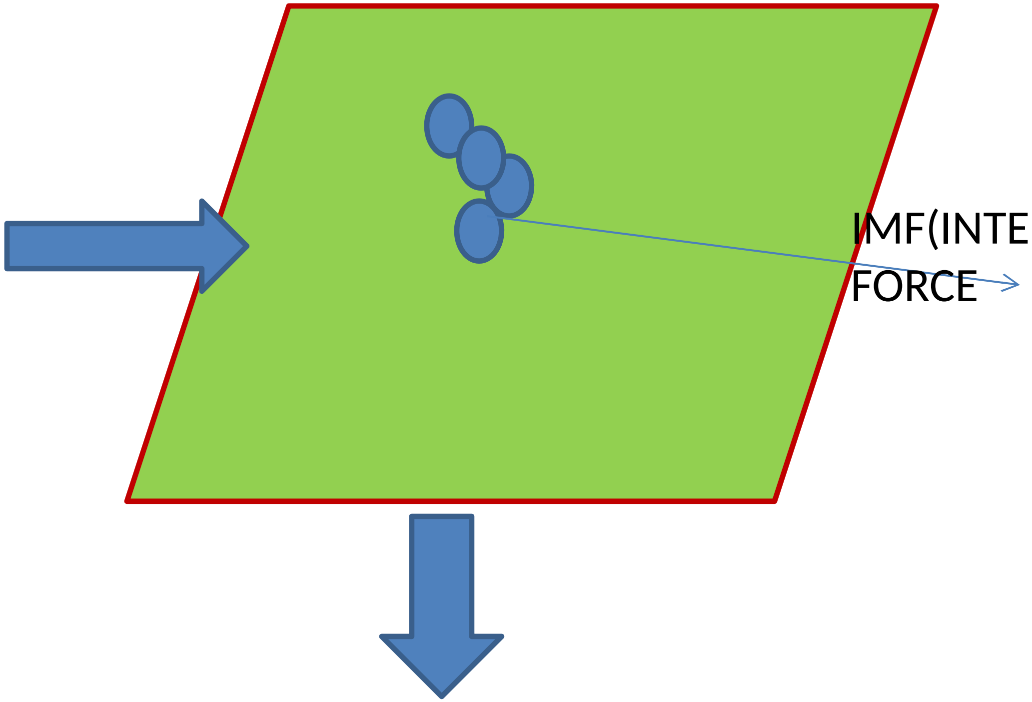
- If upon removal of load the material reverts back to its initial size – **elastic** deformation.

- If application and removal of the load results in a permanent material's shape change – **plastic** deformation.

- **Fracture** occurs when a structural component separates into two or more pieces.

- Material **failure,** i.e. an inability of a component to perform its desired function, may occur prior to fracture.

- Materials behavior (e.g. failure) depends on load ***nature*** its ***time*** schedule, and ***environmental conditions*** (e.g. temperature).



FORCE APPLIED

IMF(INTERMOLECULAR FORCE

LEADS TO CHANGE IN SHAPE OF SOLIDS

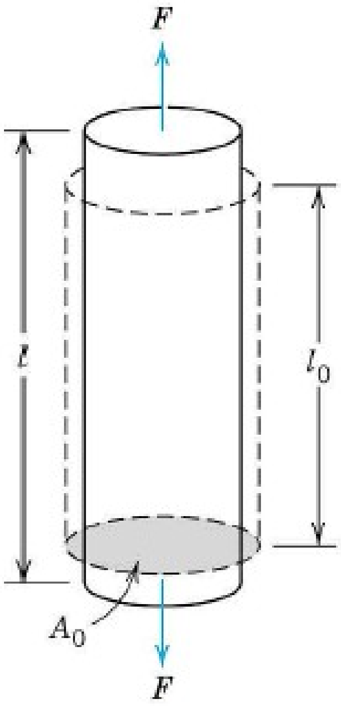
- If external force is less than intermolecular force of particular solid then there will be no deformation

- When external force is greater than intermolecular force then solid will get deformed

Types of Deformation (1)

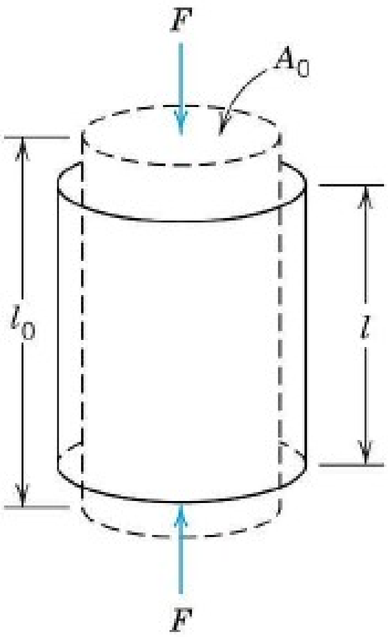
Types of loading are defined by the **direction of applied forces**

- **Elongation** – ***positive*** linear ***strain***
- **Contraction** - ***negative*** linear ***strain***



Tensile load

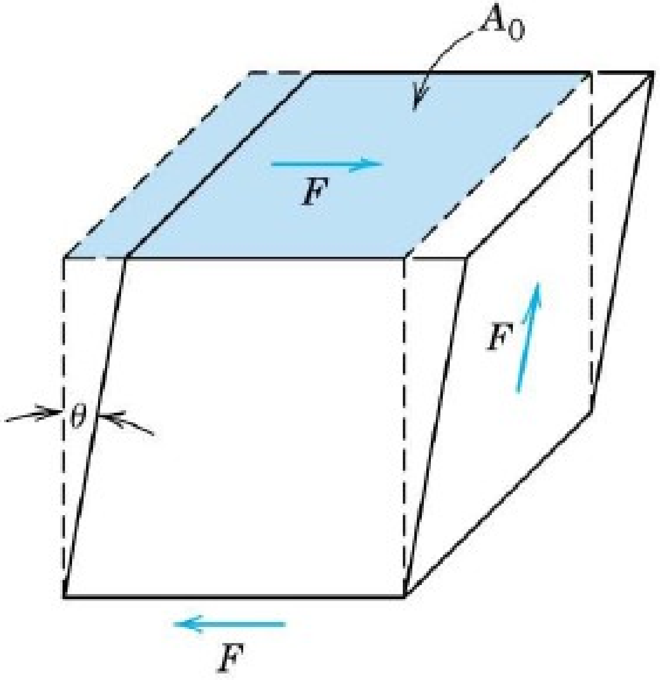
Forces applied ***normal*** to the sample surface



Compressive load

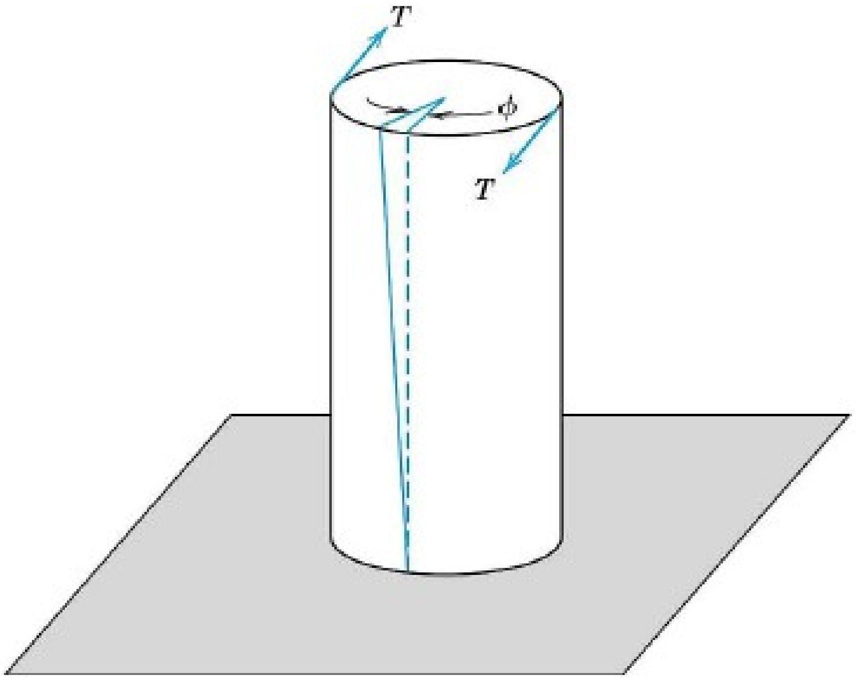
Types of Deformation (2)

- Shear ***strain***
is ~ to the *strain* angle ***q***



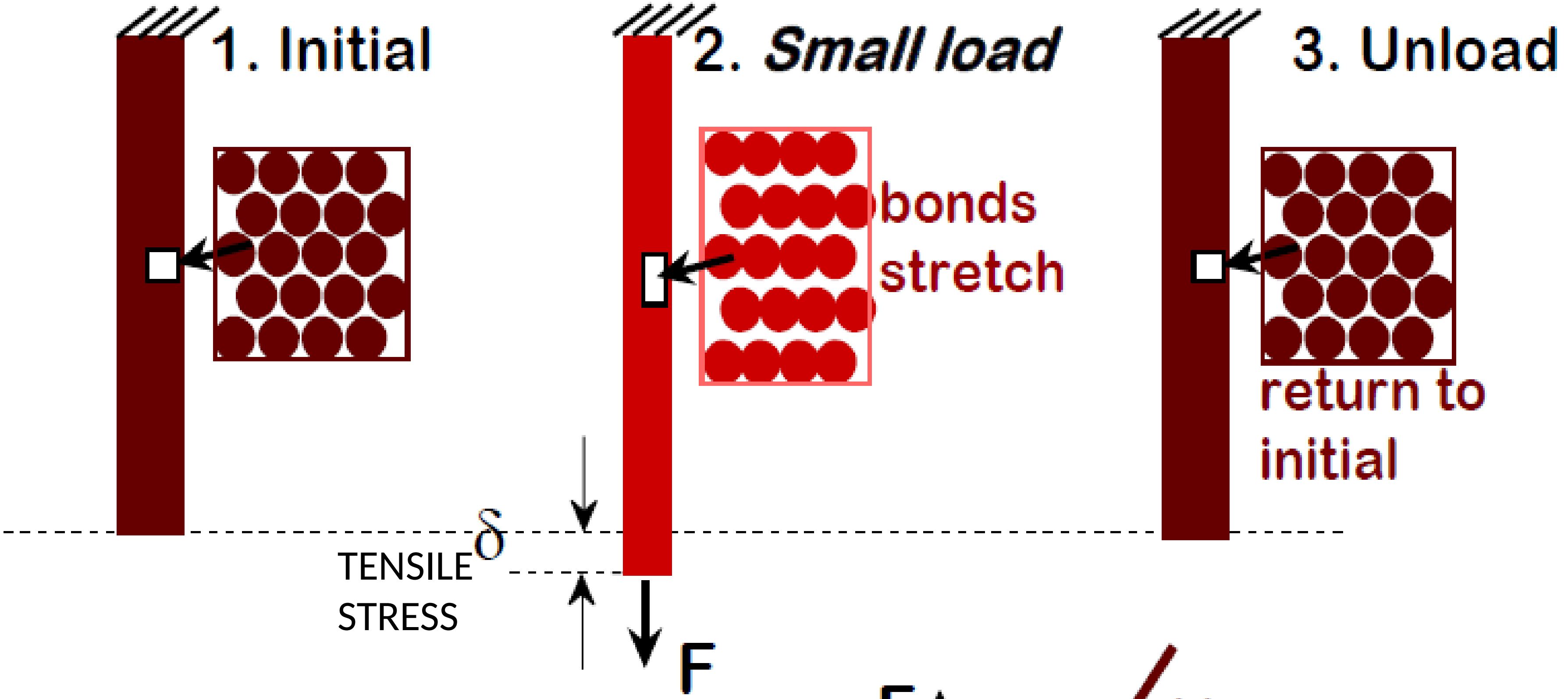
Pure shear load:
applied force is ***parallel***
to both sample faces

- ***Torsional*** deformation
is ~ to the *twist* angle, f

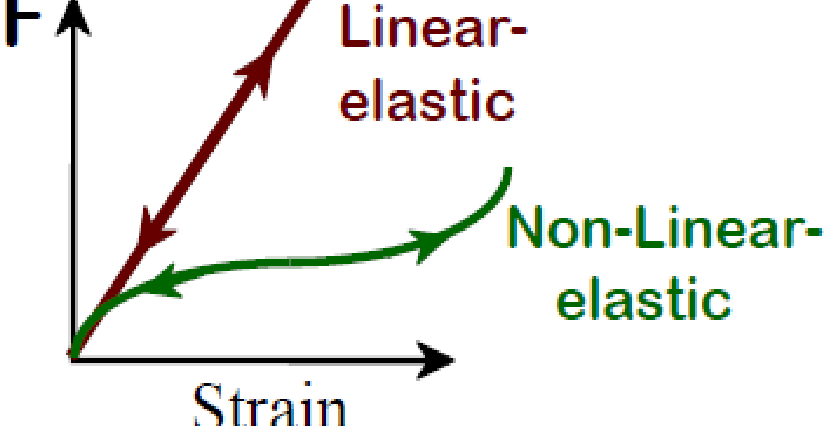


Torsion is a variation of pure shear
Torsion load produces a ***rotational motion***
(twist) around the axis of symmetry

ELASTIC DEFORMATION



Elastic means reversible!



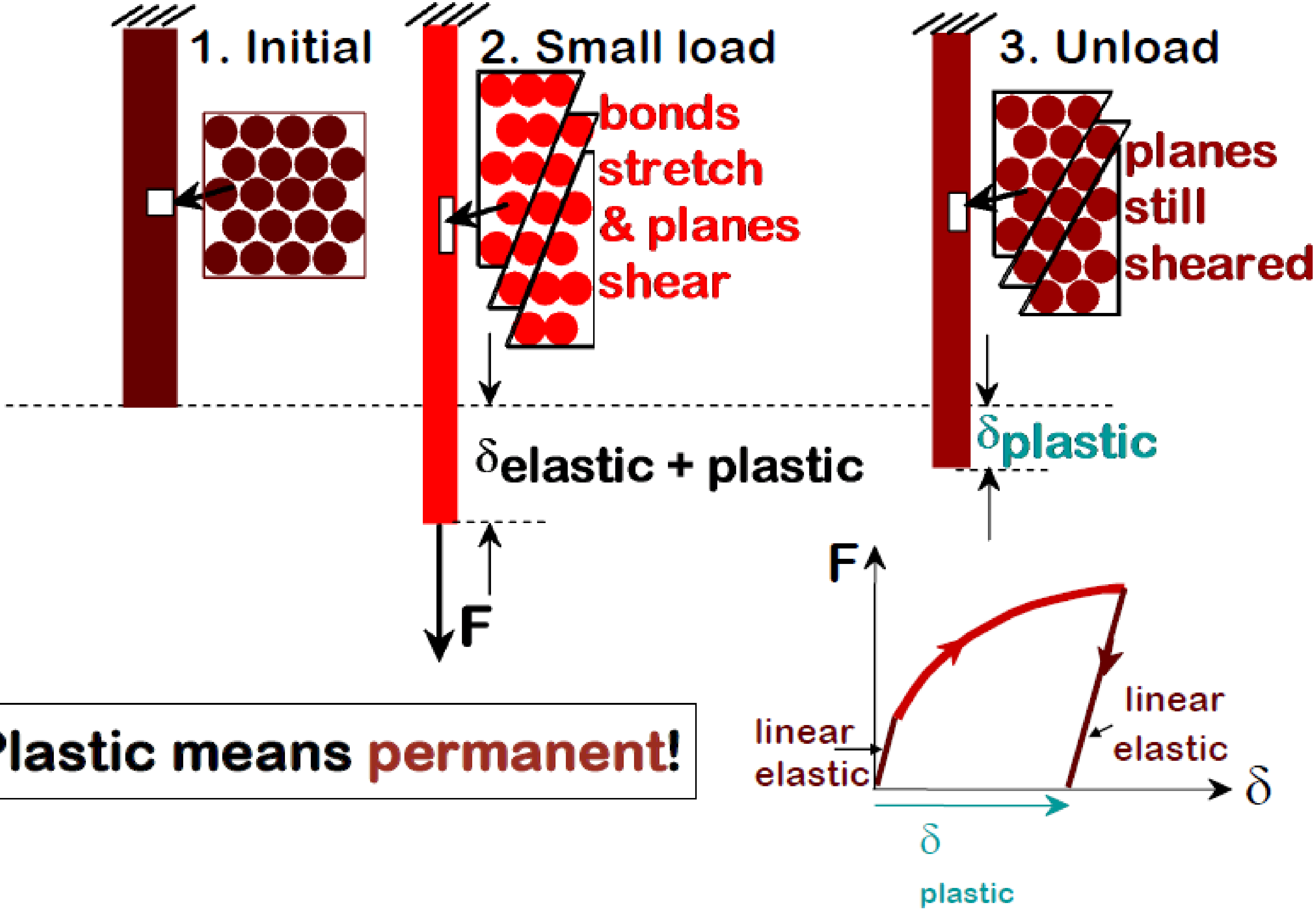
Elastic Deformation

- It is reversible.
- when the forces are removed, the object tends to its original shape.
- Elastomers and shape memory metals such as nitinol exhibit large elastic deformation ranges as does rubber. Elasticity is non linear. Metals and ceramics show linear elasticity.
- Linear elastic deformation is governed by **Hooke's Law**

$$\sigma = E \varepsilon$$

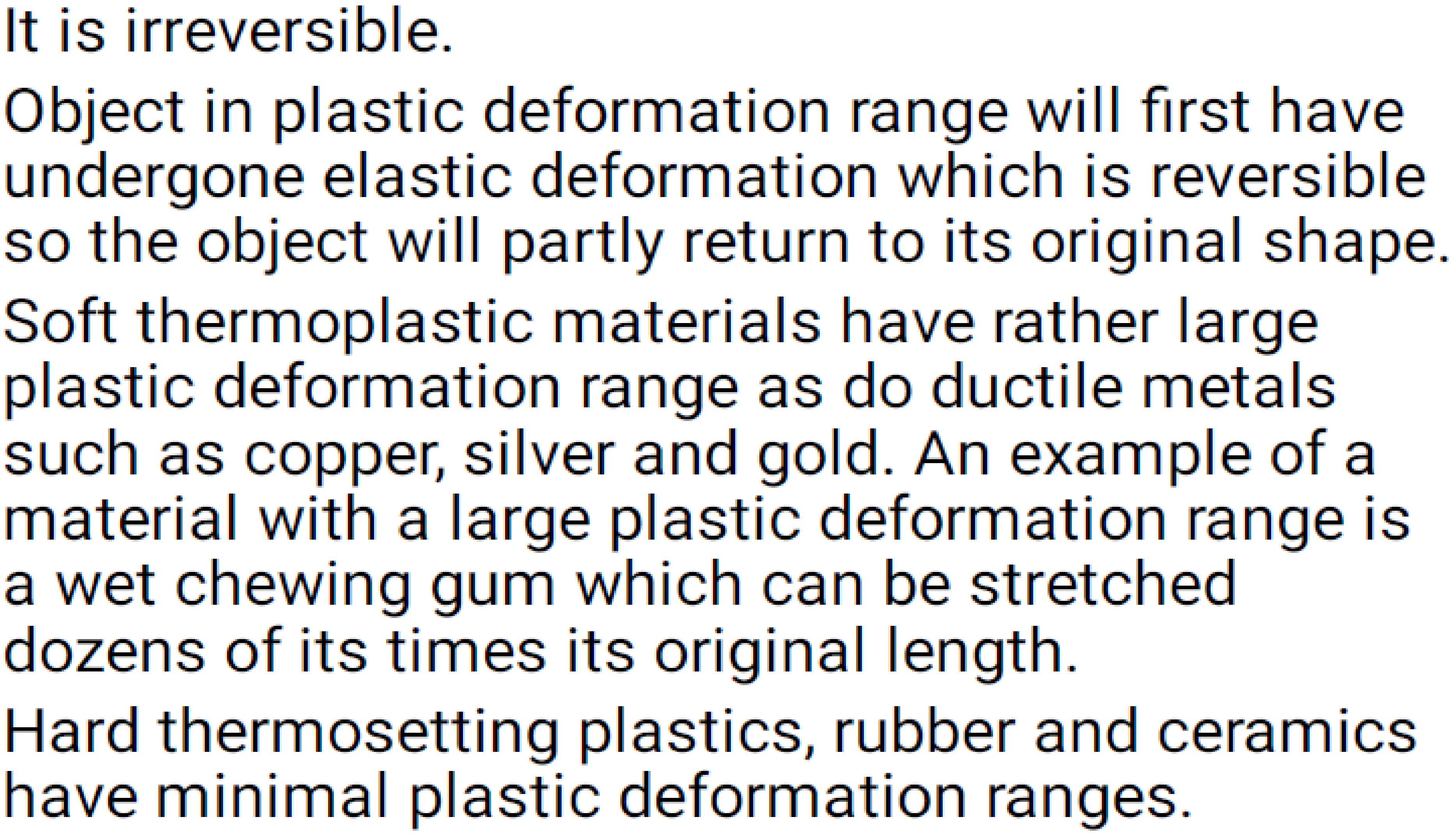
Where σ is applied stress, E is material constant called young's modulus or elastic modulus and ε is the resulting strain.

PLASTIC DEFORMATION (METALS)



Plastic means permanent!

PLASTIC DEFORMATION



It is irreversible.

Object in plastic deformation range will first have undergone elastic deformation which is reversible so the object will partly return to its original shape.

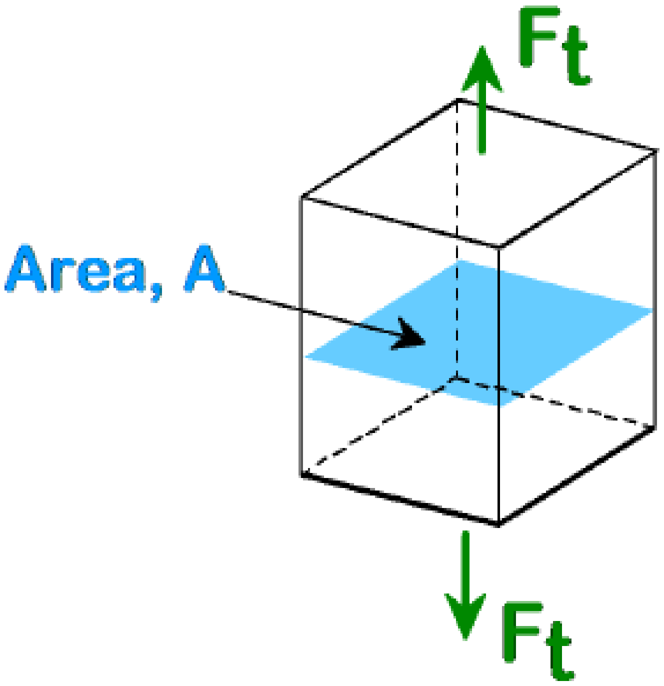
Soft thermoplastic materials have rather large plastic deformation range as do ductile metals such as copper, silver and gold. An example of a material with a large plastic deformation range is a wet chewing gum which can be stretched dozens of its times its original length.

Hard thermosetting plastics, rubber and ceramics have minimal plastic deformation ranges.

- Under the tensile stress plastic deformation is characterized as

1. **Strain hardening region** – material becomes stronger through the movement of atomic dislocations
2. **Necking region** – reduction in cross sectional area of specimen. It begins after the ultimate strength is reached. Material can no longer withstand the maximum stress and strain in the specimen rapidly increases
3. **Fracture-** indicates the end of the plastic deformation

- **Tensile stress, σ:**

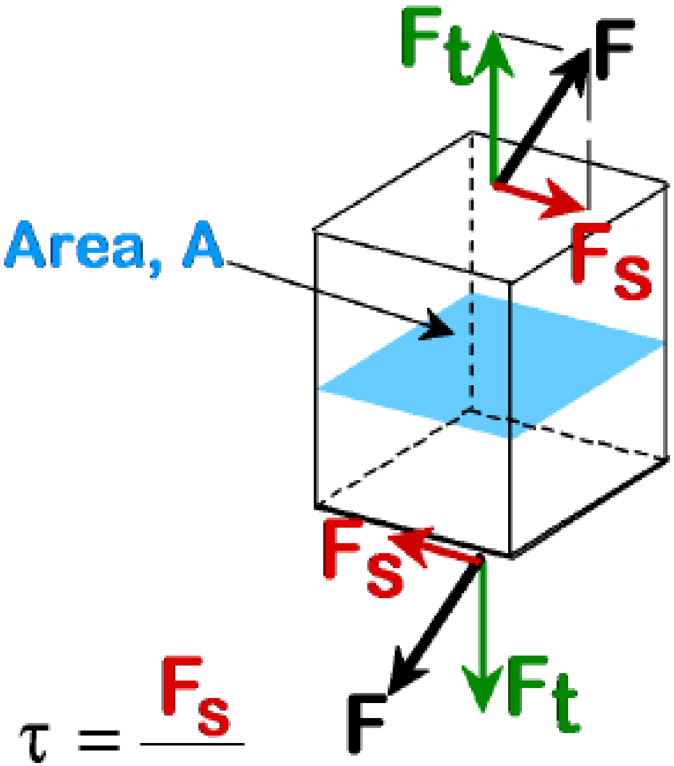


$$\sigma = \frac{F_t}{A_o}$$

Load applied *perpendicular* to the specimen cross section

original area before loading

- **Shear stress, τ:**

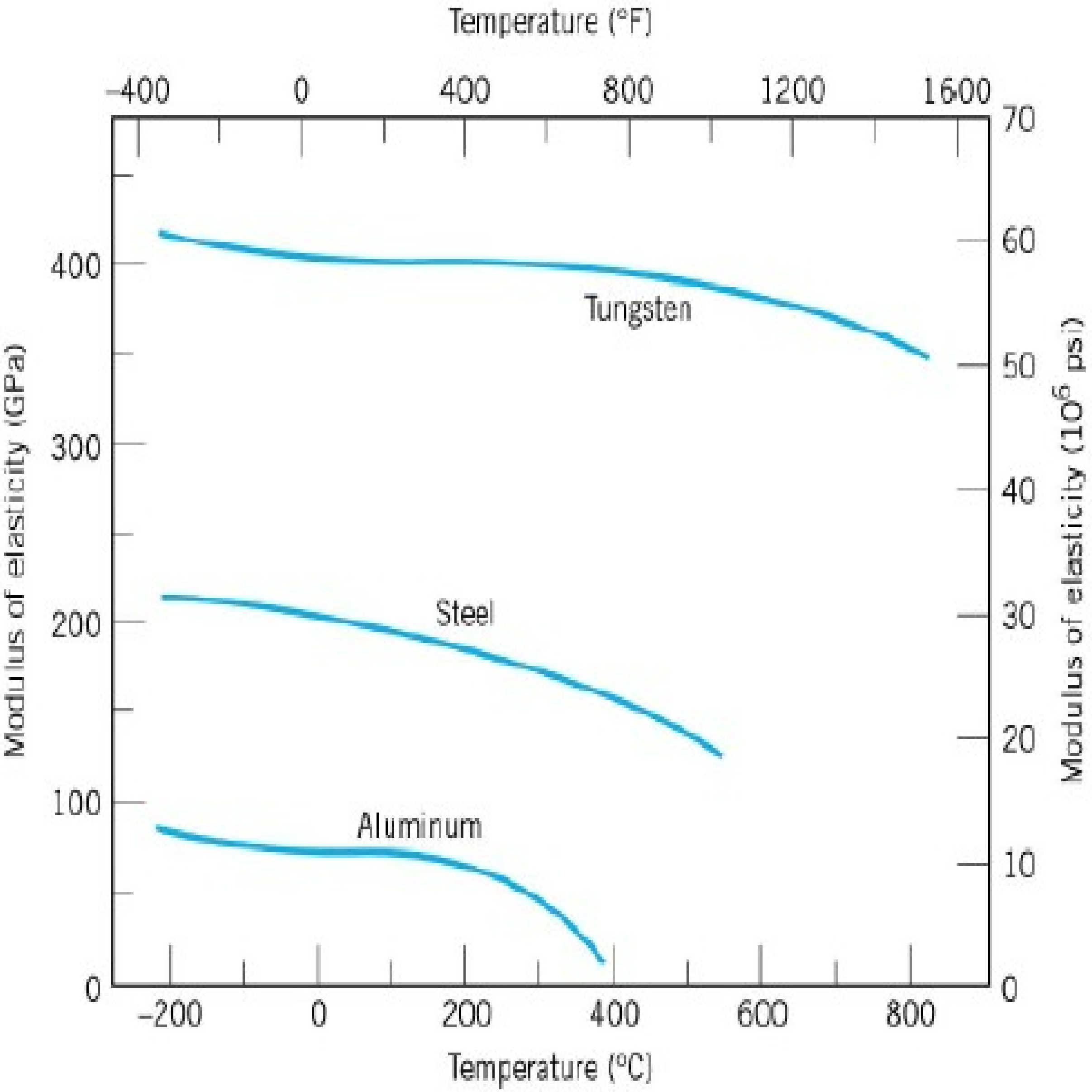


$$\tau = \frac{F_s}{A_o}$$

F_s is a load constituent *parallel* to the specimen cross section

Stress has units: N/m^2 or lb/in^2

Modulus of Elasticity for Different Metals



Elastic Modulus

- The *elastic modulus* is the constant of proportionality between stress and strain
  - For sufficiently small stresses, the stress is directly proportional to the strain
  - The constant of proportionality depends on the material being deformed and the nature of the deformation
- The elastic modulus can be thought of as the stiffness of the material
  - A material with a large elastic modulus is very stiff and difficult to deform

ELASTIC MODULUS

$$Em = \frac{\text{stress}}{\text{strain}}$$

stress is directly proportional to the young's modulus.

Higher the young's modulus higher will be the force applied example- iron .

TYPES OF ELASTIC MODULUS

1 Young's modulus

2 Bulk modulus

3 Stress and strain modulus

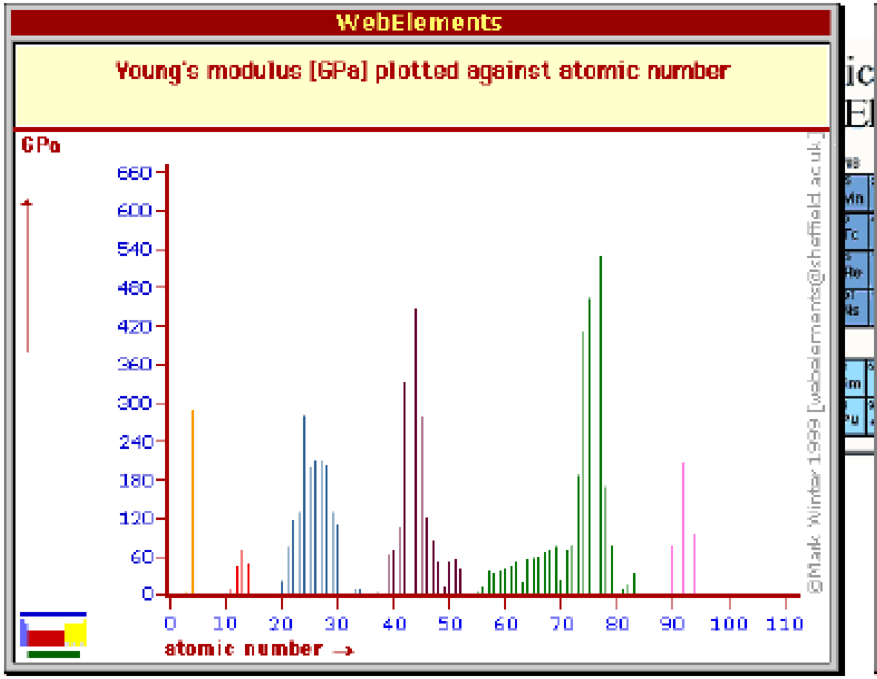
Young's Modulus

- Tensile stress is the ratio of the external force to the cross-sectional area
- SI units of stress are Pascals, Pa
    - 1 Pa = 1 N/m^2
- The tensile strain is the ratio of the change in length to the original length
    - Strain is dimensionless
    - The elastic modulus is called *Young's modulus*

$$\frac{F}{A} = Y \frac{\Delta L}{L_o}$$

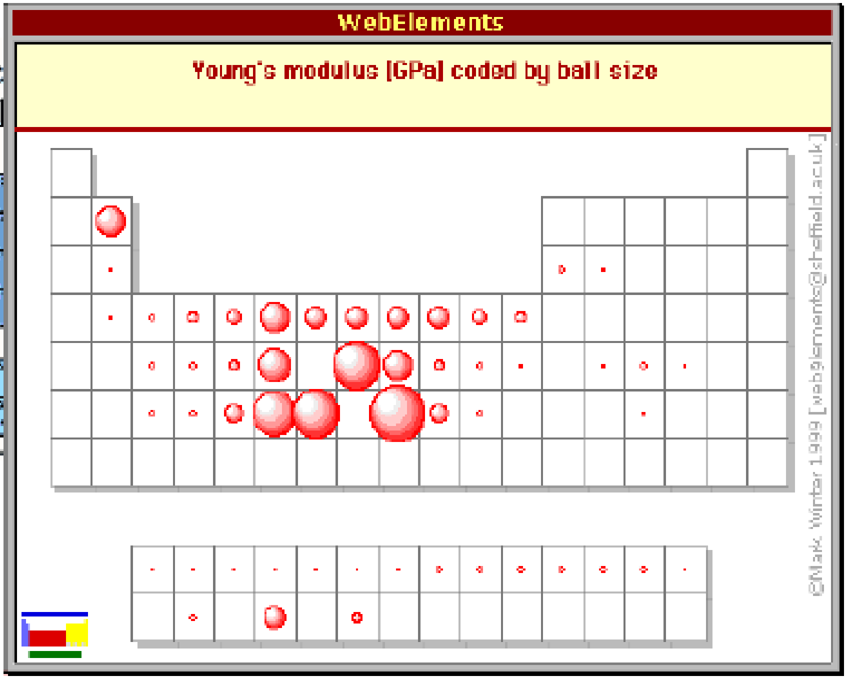
Young’s modulus

Young’s modulus is a numerical constant, named for the 18th-century English physician and physicist **Thomas Young**, that describes the elastic properties of a solid undergoing tension or compression in only one direction.



WebElements

Young's modulus [GPa] plotted against atomic number



WebElements

Young's modulus [GPa] coded by ball size

Higher E – higher “stiffness”

Bulk Modulus: Volume Elasticity

- Bulk modulus characterizes the response of an object to uniform squeezing
  - Suppose the forces are perpendicular to, and act on, all the surfaces
    - Example: when an object is immersed in a fluid
- The object undergoes a change in volume without a change in shape

$$\Delta P = -B \frac{\Delta V}{V}$$

- A material with a large bulk modulus is difficult to compress
- The negative sign is included since an increase in pressure will produce a decrease in volume
  - B is always positive
- The *compressibility* is the reciprocal of the bulk modulus

Shear Modulus

- It defines the change in shape of an object caused by pushing its top and bottom surfaces in opposite directions.
- Shear stress is the force per unit area exerted on the top and bottom of solid.
- Shear strain is the distance the top surface has moved relative to the bottom surface divided by the perpendicular distance between them.

- Shear Modulus is the ratio of shear stress to shear strain and has a unit of N/m^2.
- S = Shear stress / Shear Strain

$$= \frac{F/A}{\Delta x/h}$$

Where

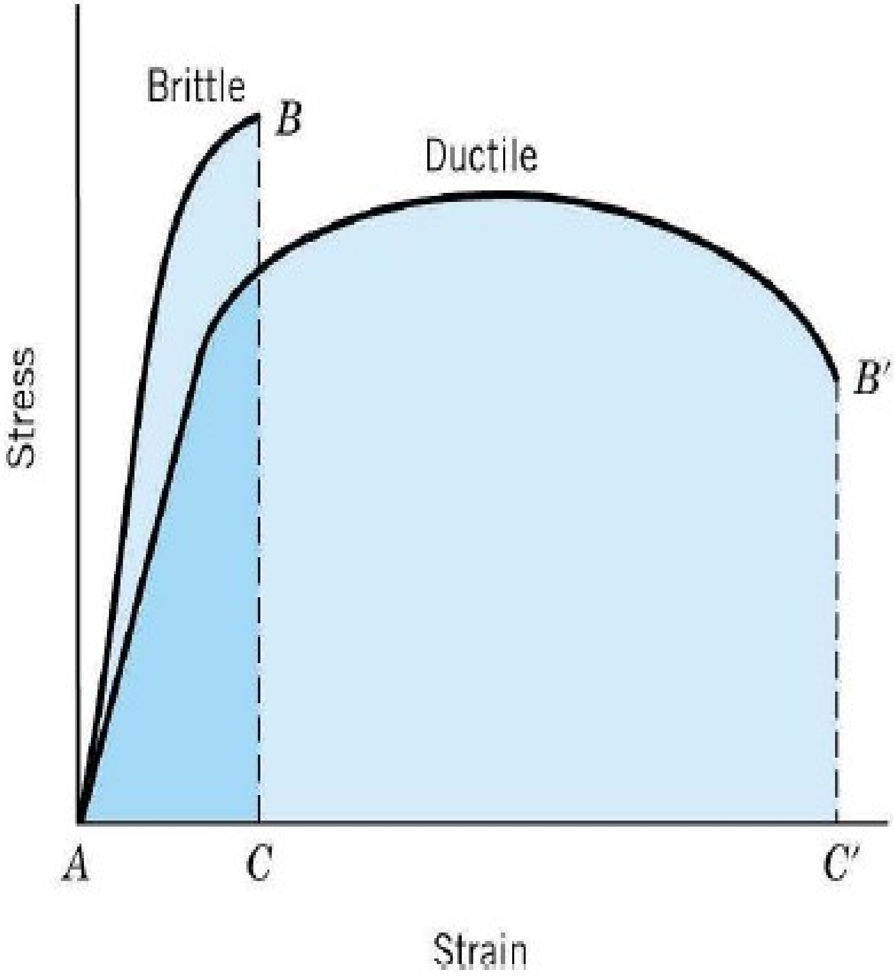
F is applied force: **A** is area, **Δx** is the distance the top surface has moved relative to bottom surface, and **h** is perpendicular distance between the top and bottom surfaces.

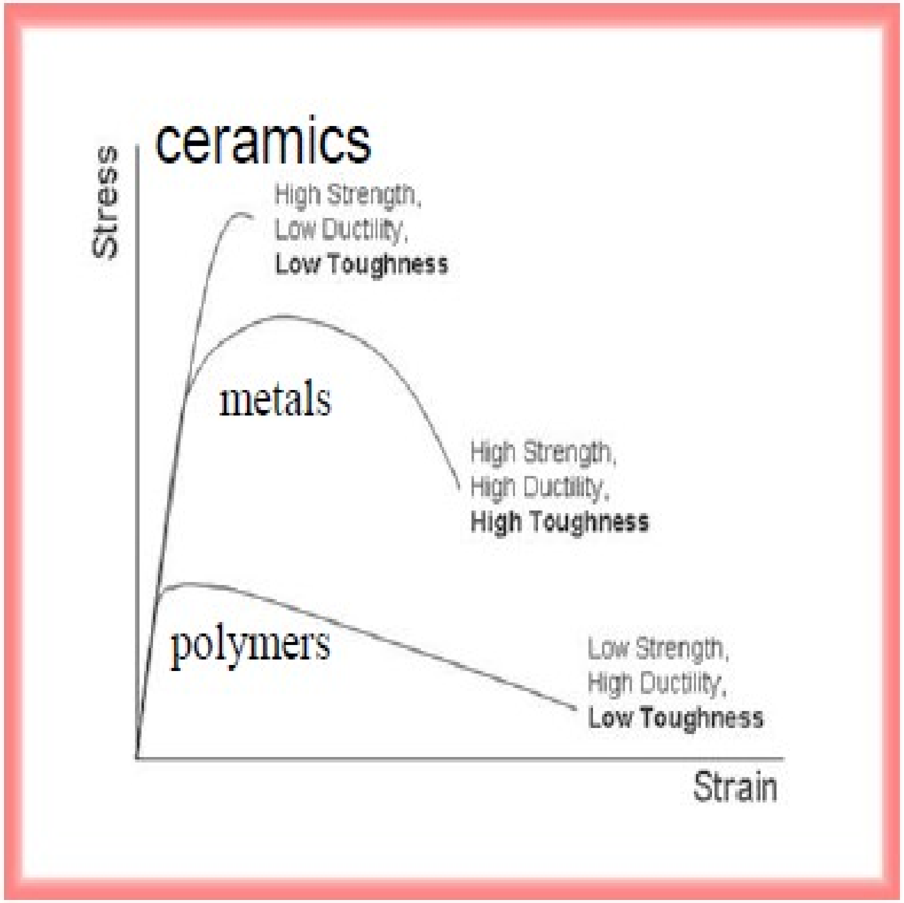
Elastic moduli:

- E = Young’s modulus (direct stress / direct strain)
- v= Poisson’s ratio (–lateral strain / direct strain)
- G = shear modulus (shear stress / shear strain)

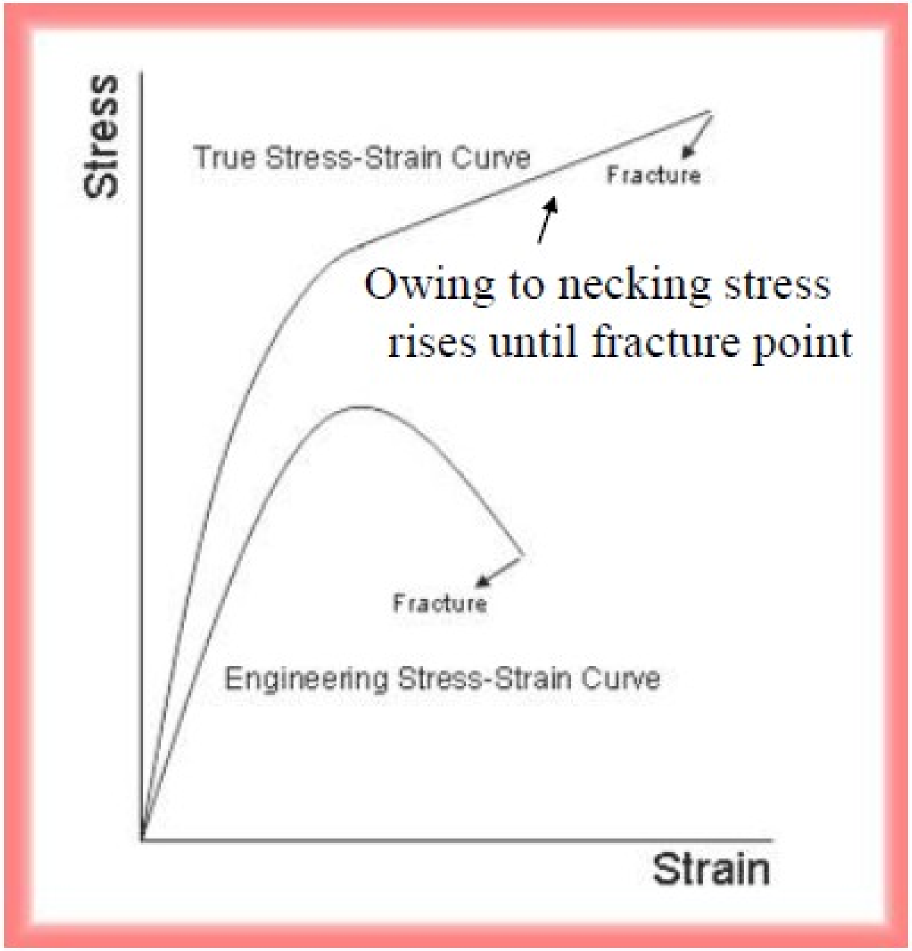
  Shear strain is Δx/l = tan θ or sometimes = θ, where θ is the angle formed by the deformation produced by the applied force.
- K = bulk modulus (average direct stress / volumetric strain)

TOUGHNESS


Brittle
B
Ductile
B′
Stress
A
C
C′
Strain


ceramics
Stress
High Strength,
Low Ductility,
Low Toughness
metals
High Strength,
High Ductility,
High Toughness
polymers
Low Strength,
High Ductility,
Low Toughness
Strain

True Stress and Strain



- **True stress**, σ_T , is defined by using instantaneous cross-sectional area of the sample, A_i

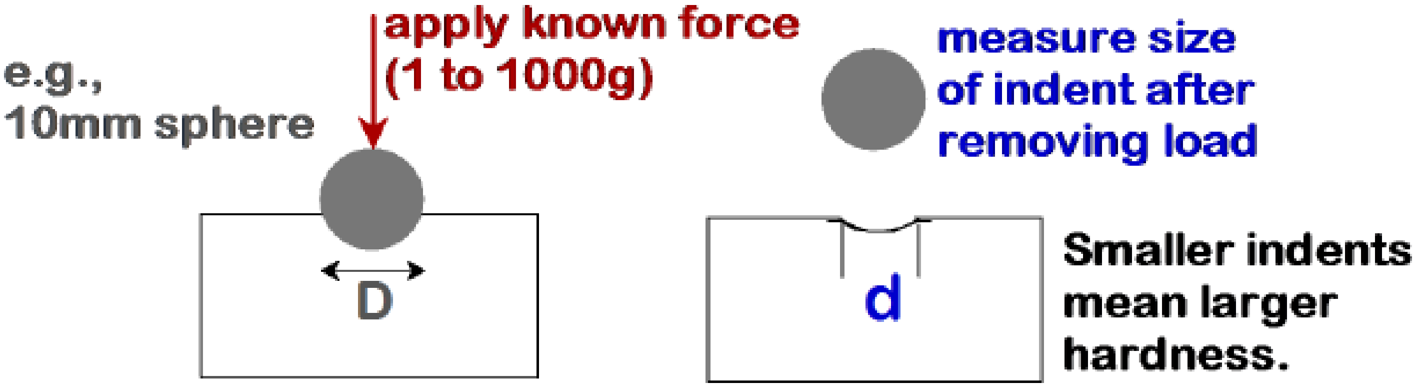
$$\boxed{\sigma_T , = F/A_i}$$

True Strain:

$$\boxed{\varepsilon_T = \ln(l_i/l_o)}$$

HARDNESS

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

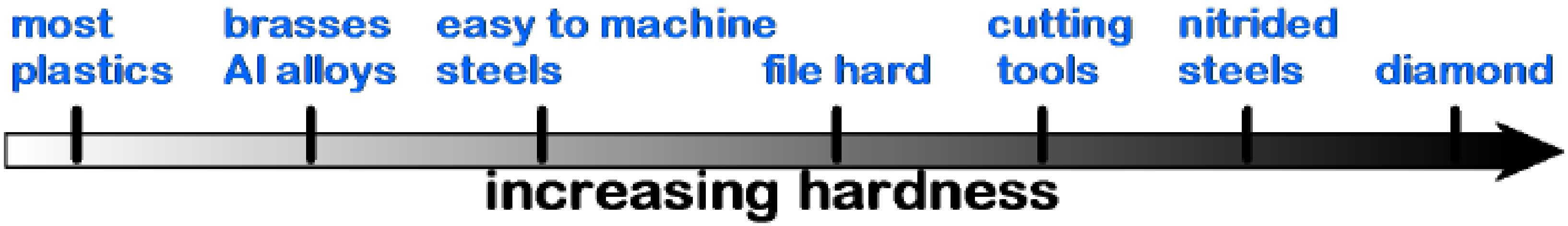


e.g., 10mm sphere

apply known force (1 to 1000g)

measure size of indent after removing load

Smaller indents mean larger hardness.



most plastics

brasses Al alloys

easy to machine steels

file hard

cutting tools

nitrided steels

diamond

increasing hardness

Heckel Equation

- The variations in volume with applied pressure are defined by way of numerous equations among which Heckel theory is most vital. Heckel measured that decline in the voids follows the first order kinetics connection with applied pressure. For compression method heckel has suggested following equation
- $\ln(V/V- V_\alpha) = KP + (V_o/ V_o- V_\alpha)$

- Where V= volume at the applied pressure P
- V_o= original volume of the powder including the voids
- V_α= volume of the powder excluding the voids
- K = constant related to the yield pressure of the powder
- P = Applied pressure

as we know **porosity E** is the ratio of the total volume of the void space to the bulk volume of the powdered material

$$E= V- V_\alpha / V$$

Replacing the value in previous equation it becomes

$$\ln(1/E) = KP + (V_o / V_o - V_\alpha)$$

Heckel Equation: The Heckel equation is based on the assumption that densification of the bulk powder under force follows first-order kinetics The Heckel equation is expressed as;

$$\ln\left[\frac{1}{1-D}\right] = KP + A$$

Heckel equation

$$\ln \frac{1}{1-D} = kP + A$$

- Heckel plot is density Vs applied pressure.
- Follows first order kinetics.
- As the porosity increases the compression force will increase.
- The Heckel equation is described as follows. It is based on the assumption that powder compression follows first-order kinetics, with the interparticulate pores as the reactant and the densification of the powder bed as the product.

- Where
  - D= relative density of a powder
  - P=compact at pressure P.
  - Constant k = measure of the plasticity of a compressed material.
  - Constant A =die filling and particle rearrangement before deformation and bonding of the discrete particles.
- Thus, a Heckel plot allows for the interpretation of the mechanism of bonding.

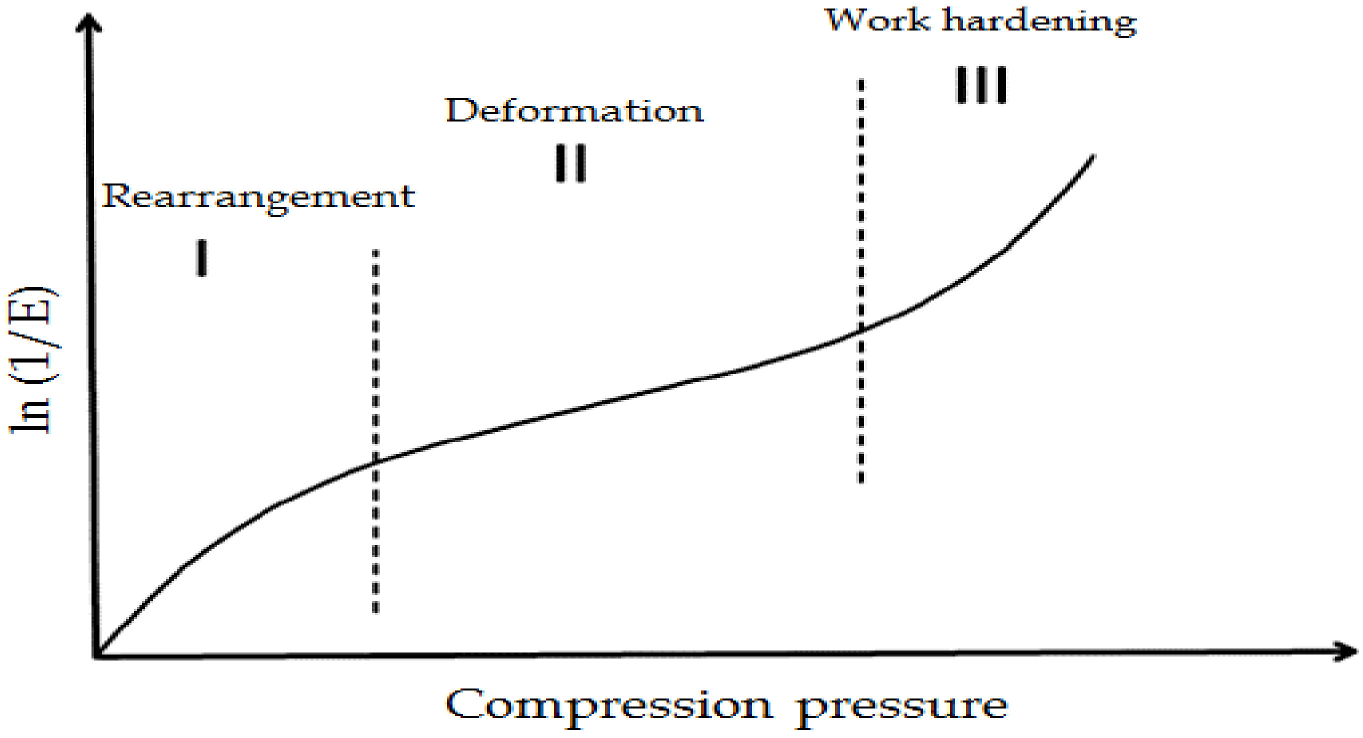
Where, *D* is the relative density of the tablet (the ratio of tablet density to true density of powder) at applied pressure *P*, and *K* is the slope of straight line portion of the Heckel plot.

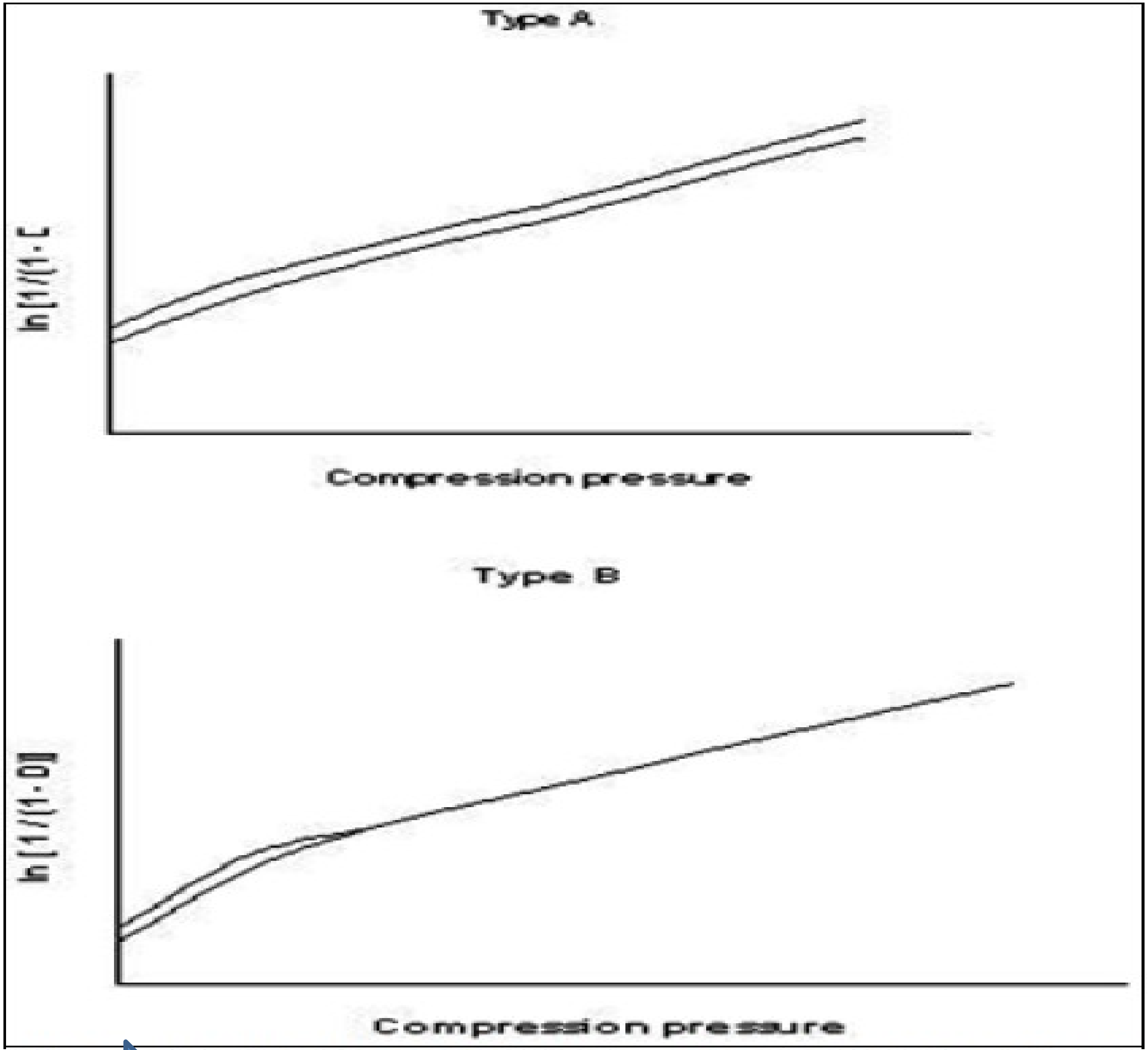
Kuentz and Leuenberger postulated a modified Heckel equation which allows the description of the transition between the states of a powder to the state of a tablet .

$$\sigma = \frac{1}{C}\left[\rho c - \rho - (1 - \rho c)\ln\left\{\frac{1-\rho}{1-\rho c}\right\}\right]$$

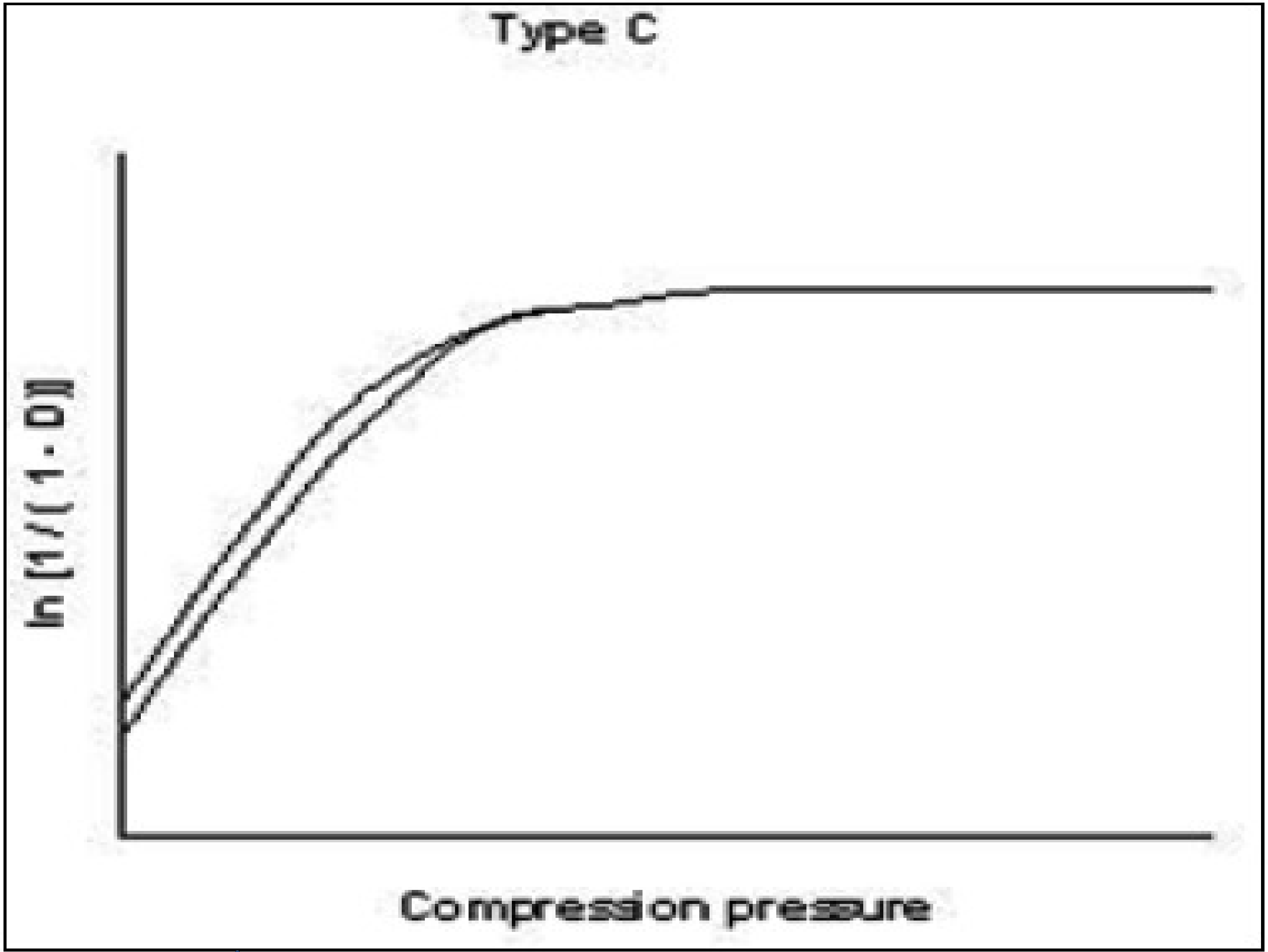
Where, σ is the pressure, ρ is the relative density, ρc is the critical density, and *C* is a constant.

A typical Heckel plot, representing three different powder compression regions





HECKLE PLOT FOR TYPE A AND TYPE B MATRIALS.



HECKLE PLOT FOR TYPE C MATRIALS

With type A materials, a linear relationship is observed, with the plots remaining parallel as the applied pressure is increased indicating deformation apparently only by plastic deformation. An example of materials that exhibit type A behavior is *sodium chloride*. Type A materials are usually comparatively soft and readily undergo plastic deformation retaining different degrees of porosity depending on the initial packing of the powder in the die. This is in turn influenced by the size distribution, shape etc. of the original particles.

For type B materials, there is an initial curved region followed by a straight line. This indicates that the particles are fragmenting at the early stages of the compression process i.e., brittle fracture precedes plastic flow. Type B Heckel plots usually occur with harder materials with higher yield pressures which usually undergo compression by fragmentation first, to provide a denser packing. Lactose is a typical example of such materials.

For type C materials, there is an initial steep linear region which become superimposed and flattens out as the applied pressure is increased. York and Pilpel ascribed this behavior to the absence of a rearrangement stage and densification is due to plastic deformation and asperity melting.

Application of Heckel equation

- The crushing strength of tablets can be correlated with the values of k of the Heckel plot .
- Larger k values usually indicate harder tablets.
- Such information can be used as a means of binder selection when designing tablet formulations.
- Heckel plots can be influenced by the overall time of compression, the degree of lubrication and even the size of the die, so that the effects of these variables are also important and should be taken into consideration.