MATERIALS inspection

Reference Text **Section**

TEXTBOOKS:

Higgins RA & Bolton, 2010. *Materials for Engineers and Technicians , 4th edition, Butterworth Heinemann* *Ch 3*

Sheedy, P. A, 1994. *Materials : their properties, testing and selection*

Byrnes, J. J, 1983. *Testing and treatment of materials*

MATERIALS TESTING

Why are metals tested ?

- Ensure quality
- Test properties
- Prevent failure in use
- Make informed choices in using materials

Factor of Safety is the ratio comparing the actual stress on a material and the safe useable stress.

Factor of Safety describes the structural capacity of a system beyond the expected loads or actual loads (The safety factor is how much the designed part actually will be able to withstand)

$$\text{factor of safety} = \frac{\text{Actual strength}}{\text{safe working stress}}$$

Two forms of tests

- **Destructive tests** (**DT**) **is called mechanical tests**. It requires destroying the specimen in order to measure the property. Often requires a specially prepared specimen. *(e.g. Tensile test).*

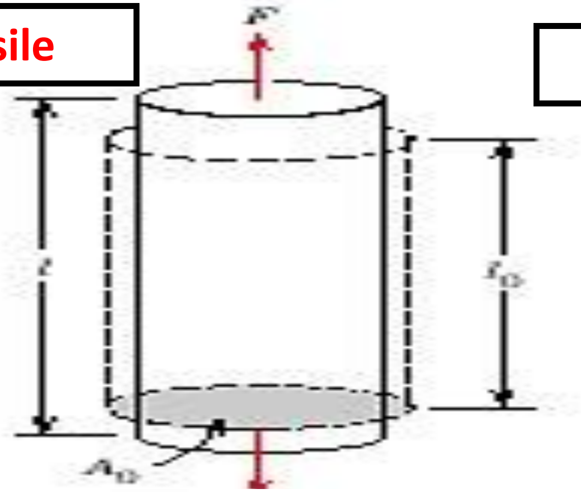
Non-destructive tests (**NDT**): measures attributes of the specimen without damaging it. Does not normally need a prepared specimen. Typically used to find flaws inside a part.
(e.g. X-ray, Ultrasound) .

Tensile Test specimens

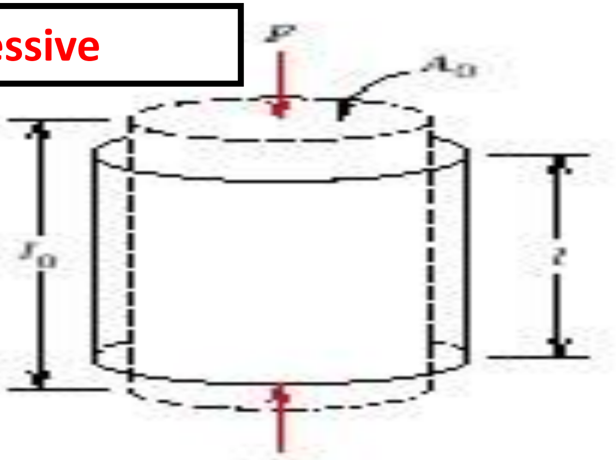
Ultrasonic Weld Inspection:

Types of Loading

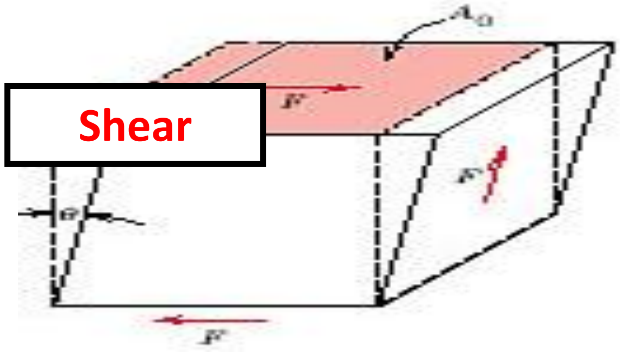
Tensile



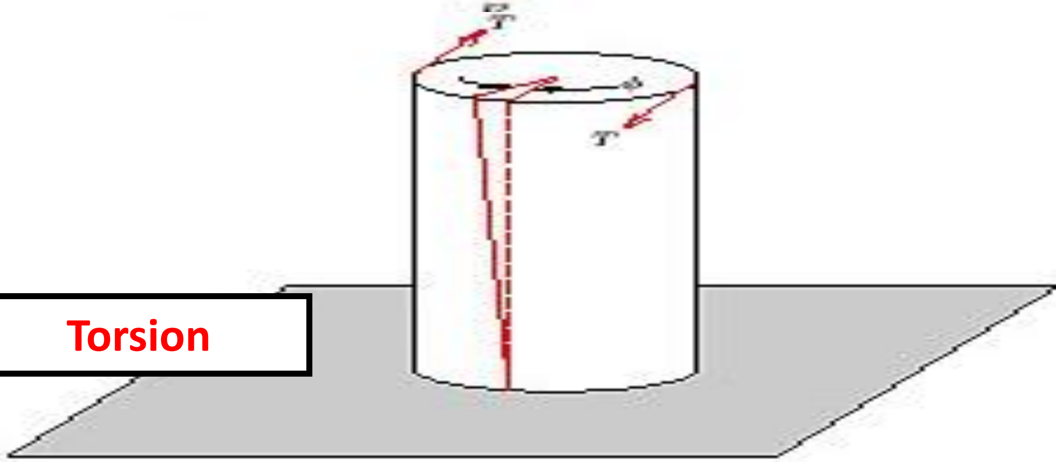
Compressive



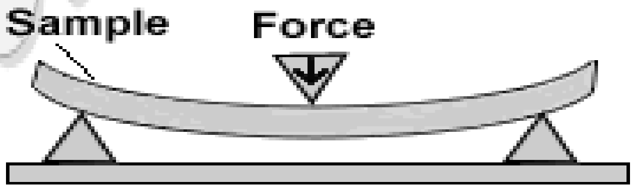
Shear



Torsion



Bending



Flexural test with three-point loading

Types of stresses

- Compressive stress
- Tensile stress
- Shear stress
- Torsion
- Bending

- **Compressive stress** is the stress applied to materials resulting in their compaction (decrease of length).

Usually compressive stress is applied to bars, columns, etc.

- **Tensile stress** is the stress state leading to expansion (length of a material tends to increase). In the uniaxial manner of tension, tensile stress is induced by pulling forces across a bar, specimen, etc.
- **Shear stress**: is a force that causes layers or parts to slide upon each other in opposite directions.
- **Torsion** the stress which resists a force tending to twist the material (e.g. axle, screw, etc.)
- **Bending** occurs when the force applied tends to pull a horizontal bar out of its straight line.

Destructive tests (DT)

- Tensile testing
- Compression testing
- Torsion testing
- Hardness testing
- Bend testing
- Impact testing
- Creep testing
- Fatigue testing
- Peel testing
- Other mechanical tests

Why use NDT?

- Components are not destroyed
- Can test for internal flaws
- Useful for valuable components
- Can test components that are in use

Six Most Common NDT Methods

- Visual Testing
- Liquid Penetrant Testing
- Magnetic Particle Testing
- Ultrasonic Testing
- Radiography Testing (X-ray Inspection)
- Eddy Current

Material properties

1. Physical properties
2. Mechanical properties
3. Chemical properties

Physical properties

- **colour** –light wave length
- **specific heat** – the heat required to raise the temperature of one gram of a substance by one degree centigrade (J/kg K)
- **density** – mass per unit volume expressed in such units as kg/cm ^{3}
- **thermal conductivity** –rate at which heat flows through a given material (W/m K)
- **melting point** – a temperature at which a solid begins to liquify
- **electrical conductivity –** a measure of how strongly a material opposes the flow of electric current (Ω·m)
- **coefficient of thermal expansion** – degree of expansion divided by the change in temperature (m/°C)

Mechanical properties

- **Tensile strength** – measures the force required to pull something such as rope,wire or a structural beam to the point where it breaks
- M**alleability** – the property of a material that can be worked or hammered or shaped without breaking
- **Ductility--**ability to deform under tensile load without rupture; high percentage elongation and percent reduction of area indicate ductility **brittleness** –breaking or shattering of a material when subjected to stress (when force is applied to it)
- **Elasticity** – the property of a material that returns to its original shape after stress (e.g. external forces) that made it deform or distort is removed
- **Plasticity** - the deformation of a material undergoing non-reversible changes of shape in response to applied forces

- **Stiffness(Rigidity)--**ability to resist deformation; proportional to Young’s Modulus E (psi) E = stress/strain (slope of linear portion of stress/strain curve).
- **Toughness** – the ability of a material to absorb energy and plastically deform without fracturing
- **Hardness** – Hardness is closely related to strength. It is the ability of a material to resist scratching, abrasion, indentation, or penetration.
- **Brittleness-** The brittleness of a material is the property of breaking without much permanent distortion. There are many materials, which break or fail before much deformation take place. Such materials are brittle e.g., glass, cast iron.
- **Machinability** –is the property of a material or a part to be machined, i.e., to remove material by cutting or abrasive processes, under given conditions

Mechanical properties	Test
Strength	Tensile/ Compression/ Shear
Stiffness	Slope of Stress-vs-Strain curve
Hardness	Rockwell / Brinell / Vickers/ Micro hardness
Toughness	Impact: Charpy / Izod

Chemical properties

- **Corrosion resistance -** a material's ability to resist deterioration caused by exposure to an environment
- **Burning (Flammability)**: A material’s ability to BURN in the presence of Oxygen

Which properties do the following materials possess?

Material	Properties
Aluminium	Lightness ; Strength
Rubber	Elasticity ; Insulation
Ceramics	Thermal Resistivity
Steel	Strength
Copper	Conductivity ; Corrosion Resistance
Lead	High Density; Ductility
Nylon	Strength ; Toughness
Wood	Insulation ; Environmental Friendliness

Find application for the following engineering materials:

Material	Application
Aluminium	Foil; Aircraft; Window Frame
Rubber	Tyres,; Seal; Gasket
Ceramics	Furnace; Brick
Steel	Section; Pipe
Copper	Pipe; Cables
Lead	Storage Battery; Radiation Protection Ballast; Bullets
Nylon	Rope; Clothing
Cast Iron	Engine Block; Valves
Wood	Furniture; Deck

Mechanical Properties

Stress and Strain

Stress: Pressure due to applied load.

Area

$$\boxed{stress = \sigma = \frac{force}{area}}$$

tension, compression, shear, torsion, and combination.

Strain: response of the material to stress (i.e. physical deformation such as elongation due to tension).

COMMON STATES OF STRESS

- Simple tension: cable

A_o = cross sectional Area (when unloaded)

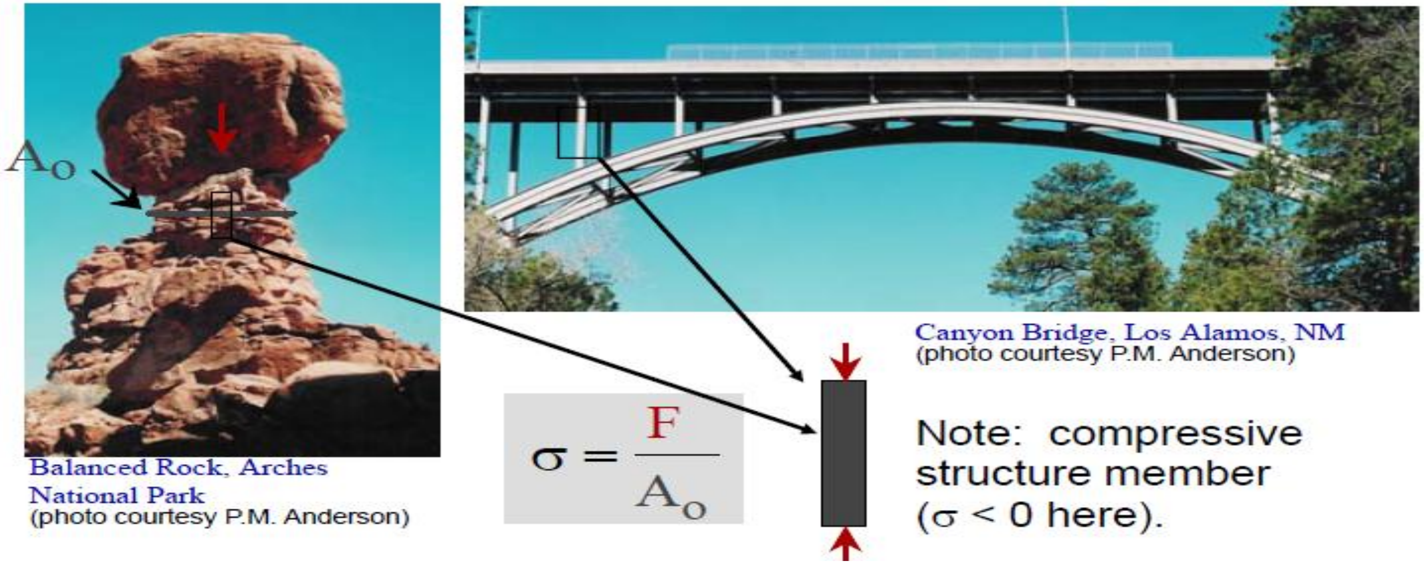
$$\sigma = \frac{F}{A_o}$$

Ski lift (photo courtesy P.M. Anderson)

From Callister 6e resource CD.

COMMON STATES OF STRESS

- Simple compression:



Balanced Rock, Arches National Park
(photo courtesy P.M. Anderson)

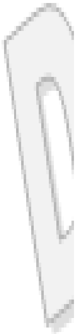
Canyon Bridge, Los Alamos, NM
(photo courtesy P.M. Anderson)

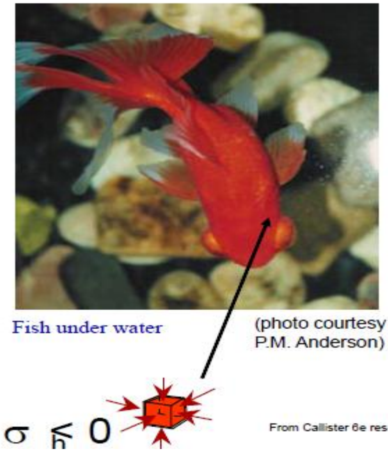
$$\sigma = \frac{F}{A_o}$$

Note: compressive structure member ($\sigma < 0$ here).

COMMON STATES OF STRESS

- Hydrostatic compression:





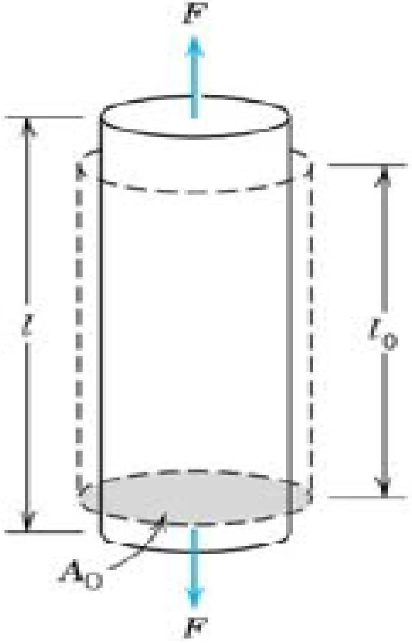
Fish under water

(photo courtesy P.M. Anderson)

$\sigma_h < 0$

From Callister 6e resource CD.

Tension



Engineering stress = $\sigma = \dfrac{F}{A_o}$

Engineering strain = $\varepsilon = \dfrac{l_i - l_o}{l_o} = \dfrac{\Delta l}{l_o}$

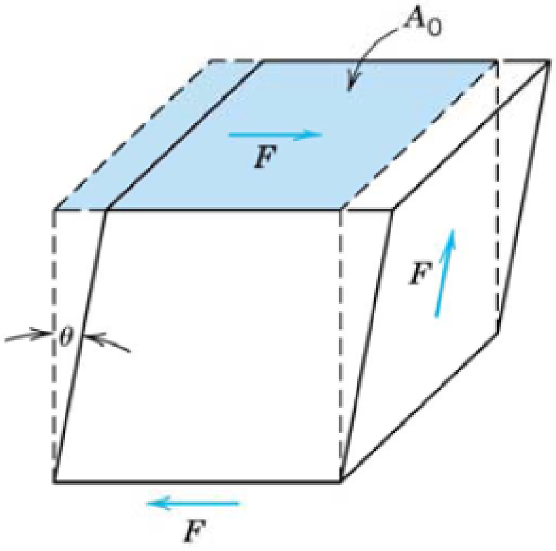
A_o = original cross sectional area
l_i = instantaneous length
l_o = original length
Note: strain is unitless.

Stress has units:
SI unit: N/m^2 (Pa, Pascal), or N / mm^2 (MPa),
1 MPa = 10^6 Pa, 1 GPa = 10^9 Pa
US : lb/in^2 1 N = 1 kg·m/s^2 = 0.2248 lb

Compression

Same as tension but in the opposite direction (stress and strain defined in the same manner).
By convention, stress and strain are negative for compression.

Shear



Pure shear stress = $\tau = \dfrac{F}{A_o}$

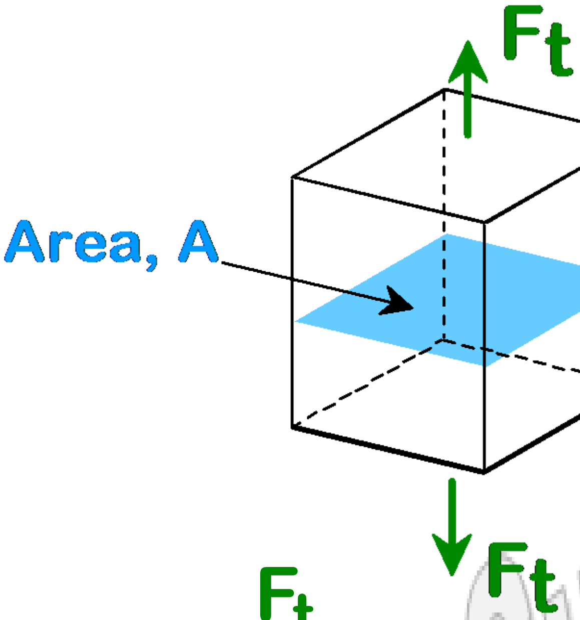
Pure shear strain = $\gamma = \tan\theta$

for a force $P = 27$ kN acts on a round bar with $d = 50$ mm, the stress is

$$\sigma = \frac{P}{A} = \frac{P}{\pi\, d^2/4} = \frac{27\ \text{kN}}{\pi\,(50\ \text{mm})^2/4} = 13.8\ \text{MPa}$$

ENGINEERING STRESS

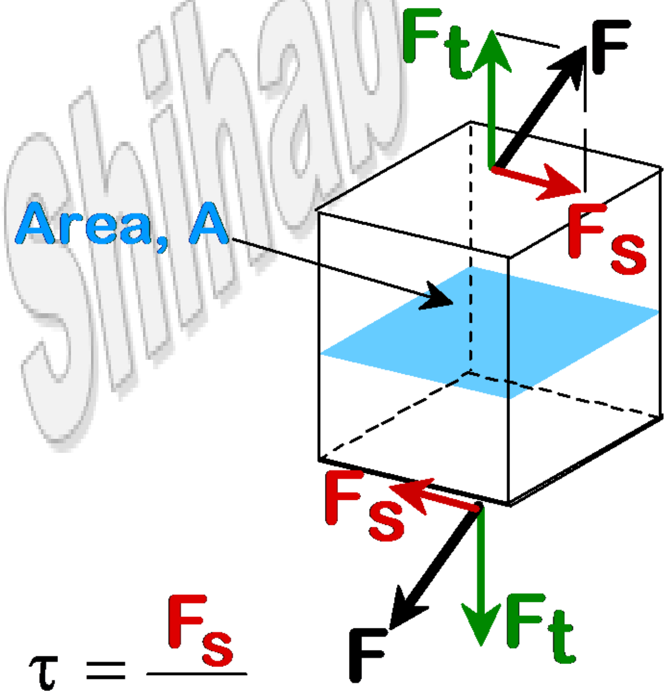
- **Tensile** **stress, σ:**



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

original area before loading

- **Shear** **stress, τ:**

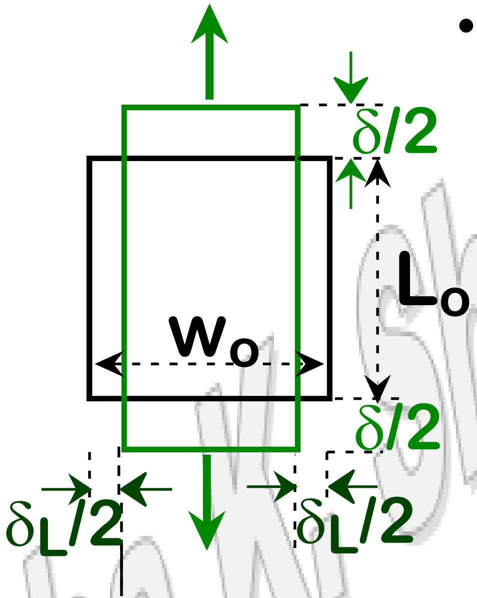


$$\tau = \frac{F_s}{A_o}$$

ENGINEERING STRAIN

- **Tensile strain:**

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

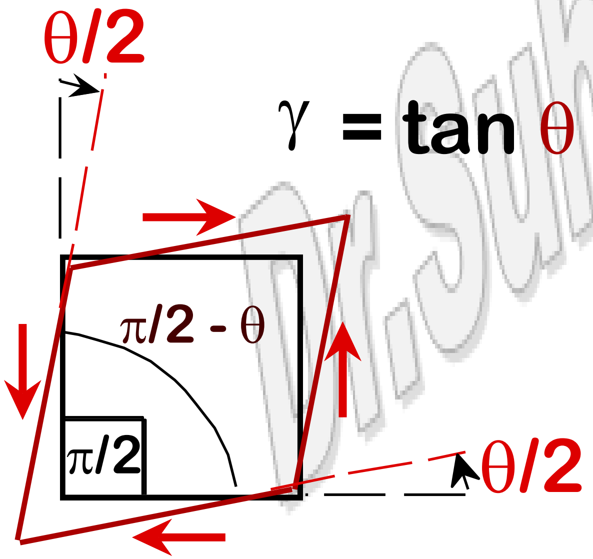


- **Lateral strain:**

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

Strain is always dimensionless.

- **Shear strain:**



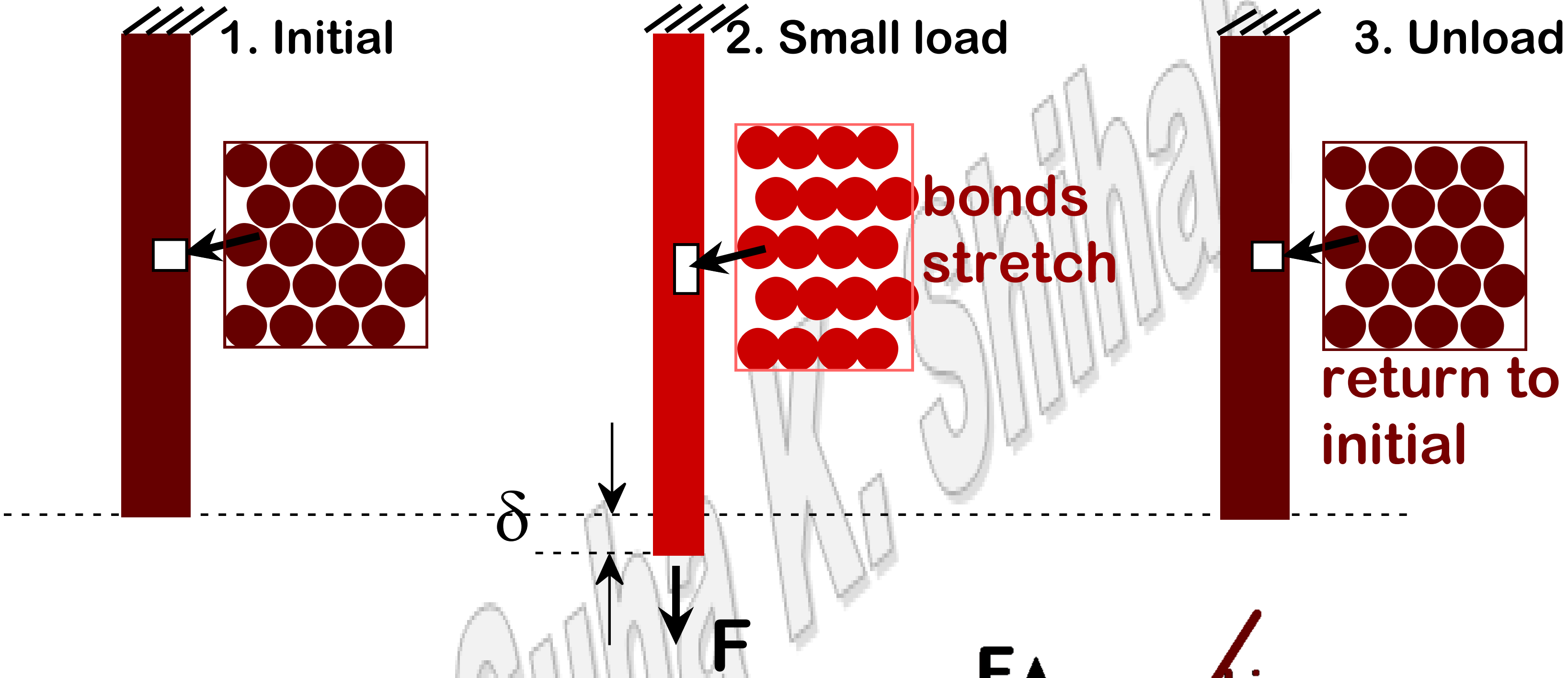
$$\gamma = \tan\theta$$

$$\text{e.g. } L = 2\text{ m},\quad \delta = 1.4\text{ mm}$$

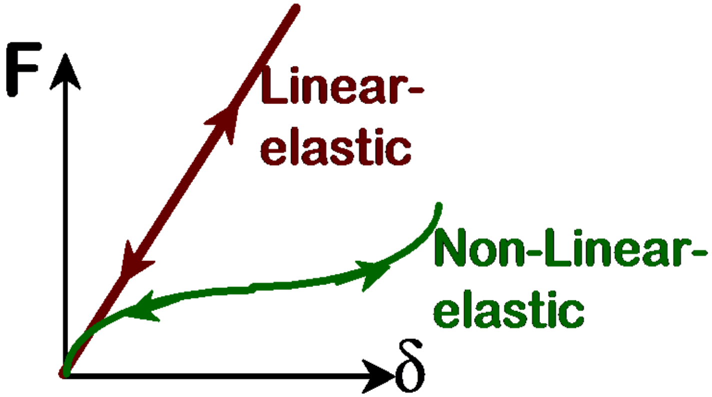
$$\text{then}\quad \varepsilon = \frac{1.4 \text{ x } 10^{-3}\text{ m}}{2\text{ m}} = 0.0007 = 0.7\text{ mm/m}$$

$$= 700 \text{ x } 10^{-6} = 700\ \mu\text{m/m} = 0.07\%$$

ELASTIC DEFORMATION

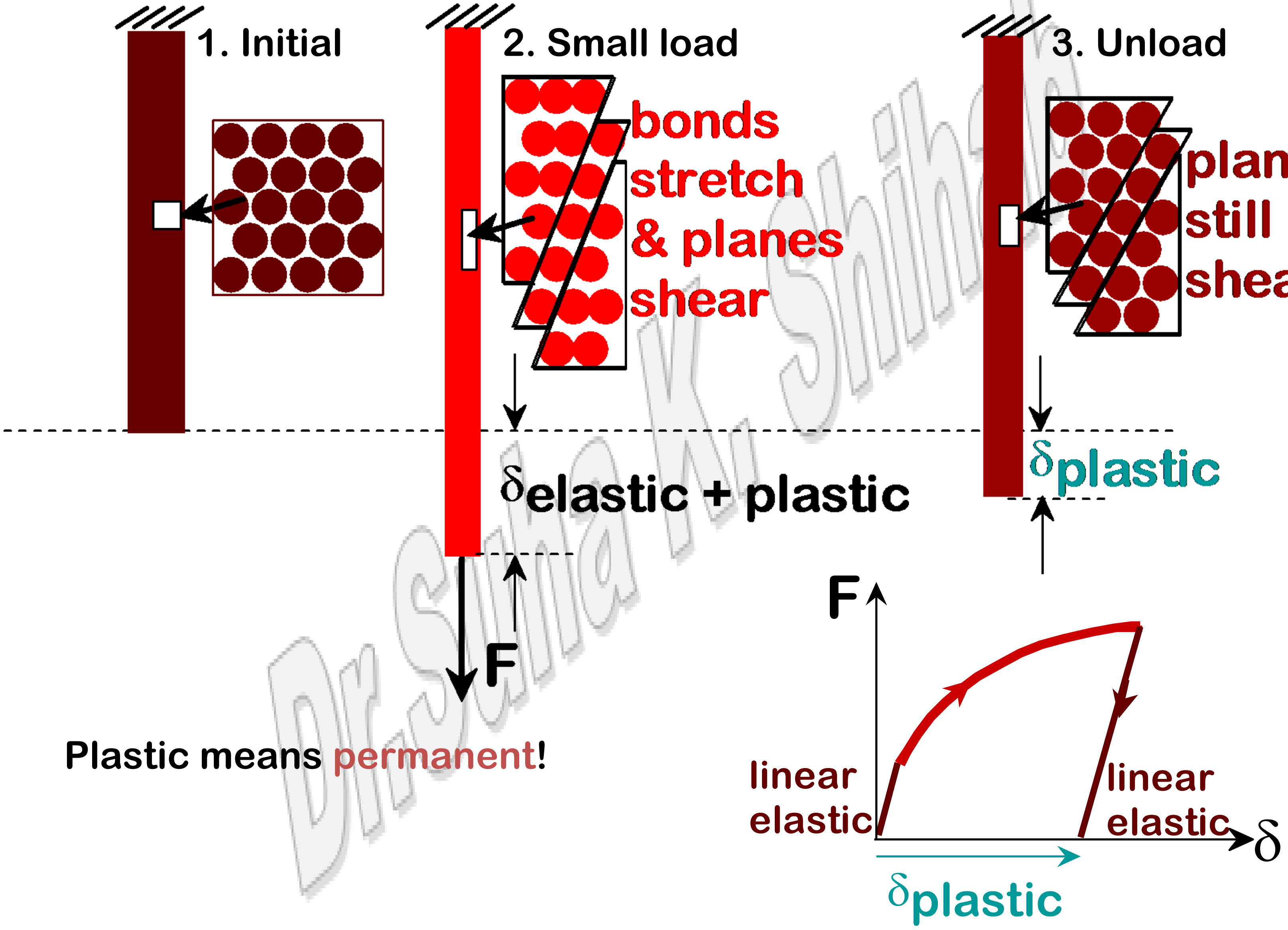


Elastic means reversible!



ELASTIC DEFORMATION: is a non-permanent deformation where the material completely recovers to its original state upon release of the applied stress.

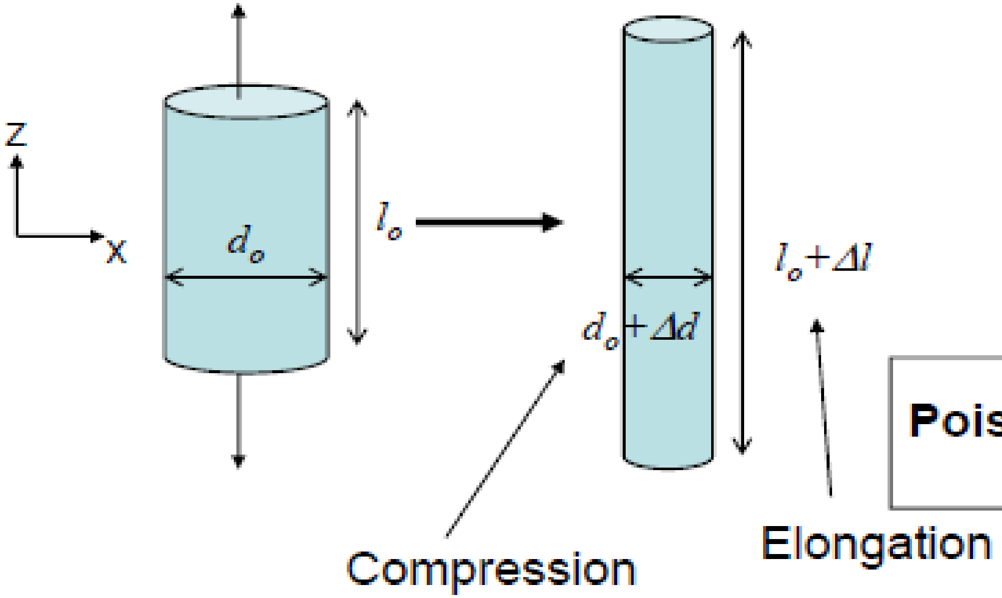
PLASTIC DEFORMATION (METALS)



Plastic means permanent!

Poisson Ratio

So far, we've considered stress only along one dimension…



Along z: tension $\varepsilon_z = \dfrac{\Delta l}{l_o}$

Along x: compression $\varepsilon_x = \dfrac{\Delta d}{d_o}$

Isotropic x and y: $\varepsilon_y = \varepsilon_x$

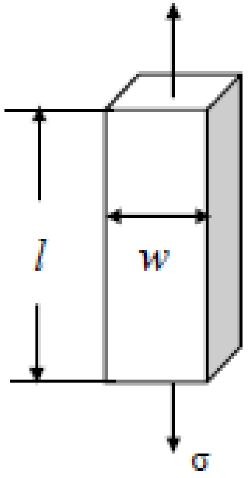
Poisson ratio = $\upsilon = -\dfrac{\varepsilon_x}{\varepsilon_z} = -\dfrac{\varepsilon_y}{\varepsilon_z}$

Relation between elastic and shear moduli: $E = 2G(1+\nu)$

when the properties of a material are the same in all directions, the material is said to be **isotropic.** So**, Isotropy** is uniformity in all orientations.
When the properties of a material vary with different crystallographic orientations, the material is said to be **anisotropic**.

Poisson Ratio

- *Poisson Ratio has a range* $-1 \le \nu \le 1/2$



Look at extremes $\Delta w/w = \Delta\ell/\ell$

- No change in aspect ratio:

$$\nu = -\frac{\Delta w/w}{\Delta\ell/\ell} = -1$$

- Volume ($V = AL$) remains constant: $\Delta V = 0$ or $l\Delta A = -A\,\Delta l$

Hence, $\Delta V = (l\,\Delta A + A\,\Delta l) = 0$.

In terms of width, $A = w^2$,

and $\Delta A = w^2 - (w+\Delta w)^2 = 2w\,\Delta w + \Delta w^2$

then

$$\Delta A/A = 2\,\Delta w/w + \Delta w^2/w^2$$

in the limit of small changes,

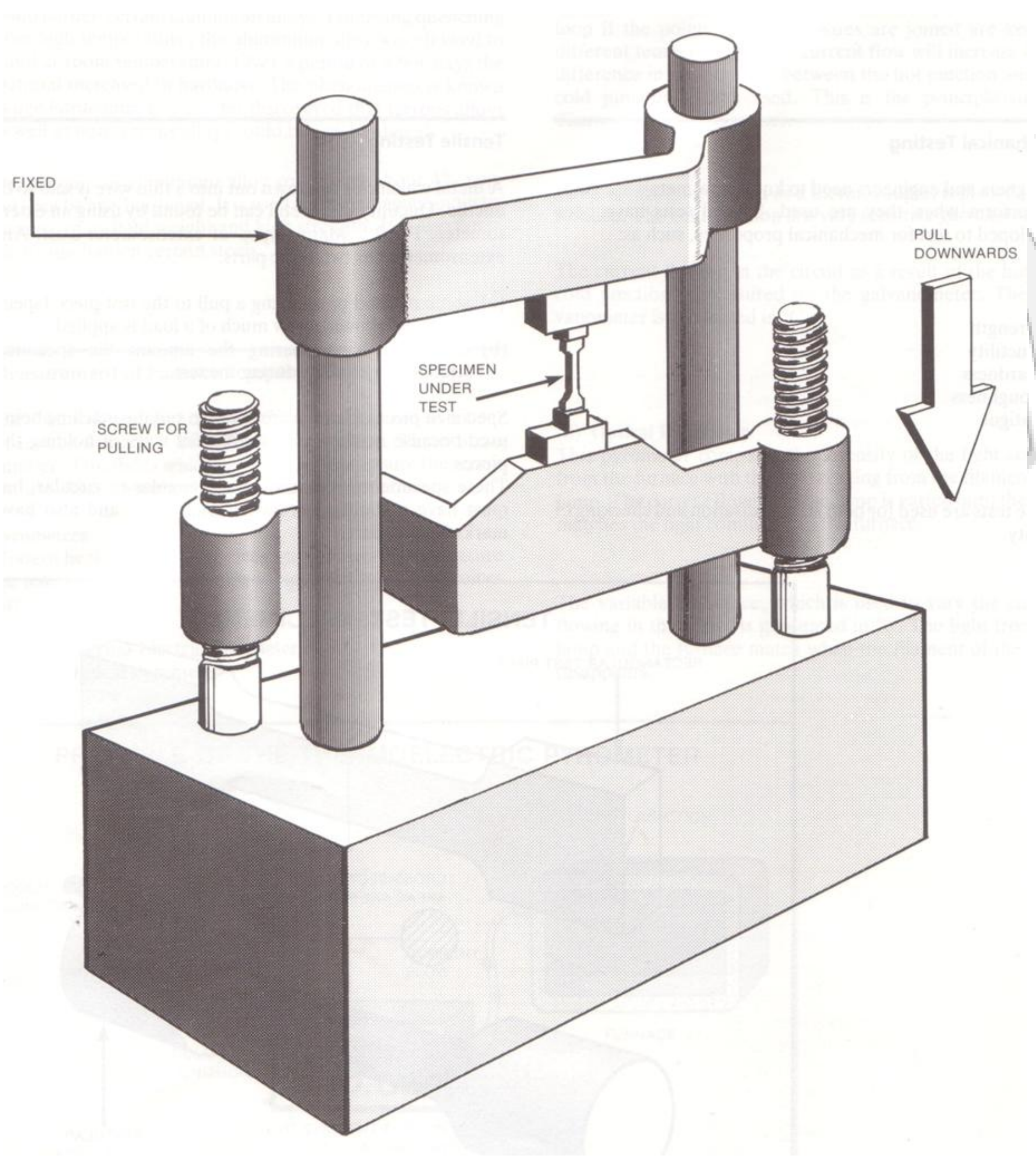
$$\Delta A/A = 2\,\Delta w/w$$

then

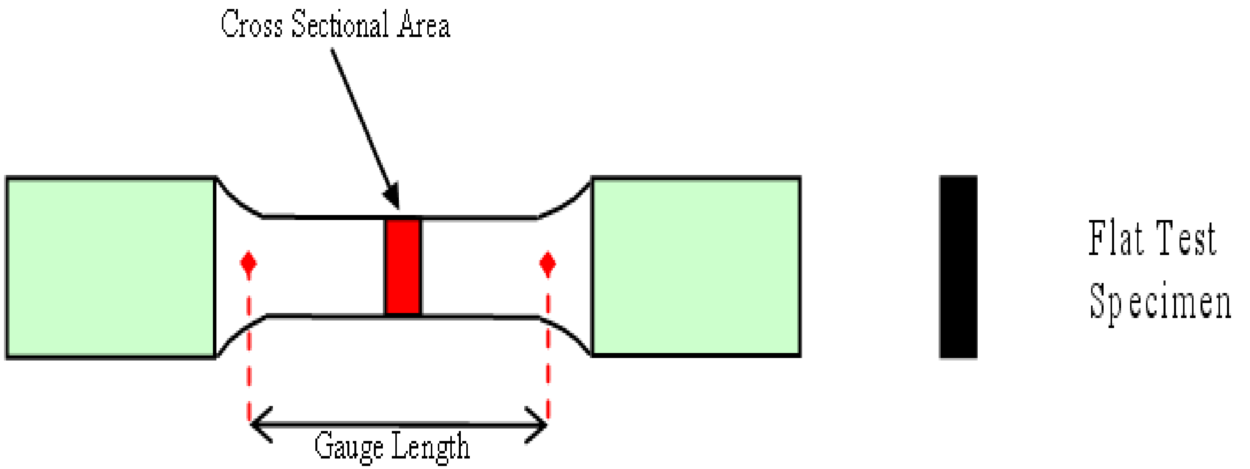
$$2\,\Delta w/w = -\Delta l/l$$

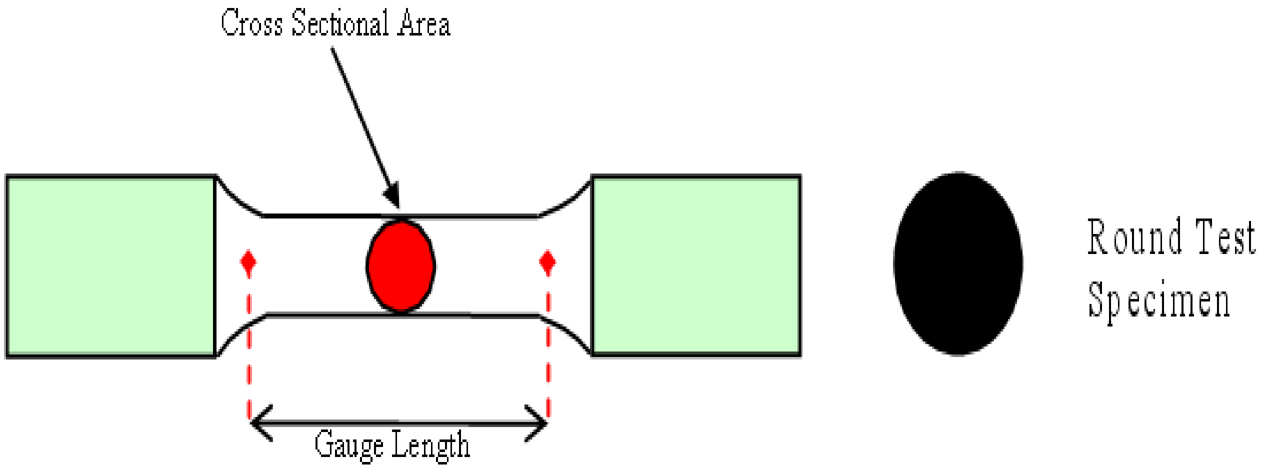
$$\nu = -\frac{\Delta w/w}{\Delta\ell/\ell} = -\frac{(-\frac{1}{2}\Delta\ell/\ell)}{\Delta\ell/\ell} = 1/2$$

Extensometer



Tensile tests are usually done on prepared





- When a material fails to return to its original length it has reached its ***elastic limit*** or *limit of proportionality*. So ***elastic limit*** is the highest magnitude of stress for which the stress and strain are proportional to each other.

- After the elastic limit the loads produce much larger extensions of the specimen. This is called the ***plastic region***.

- At the end of this stage, the extension is even greater and **a** ***yield point*** is reached.

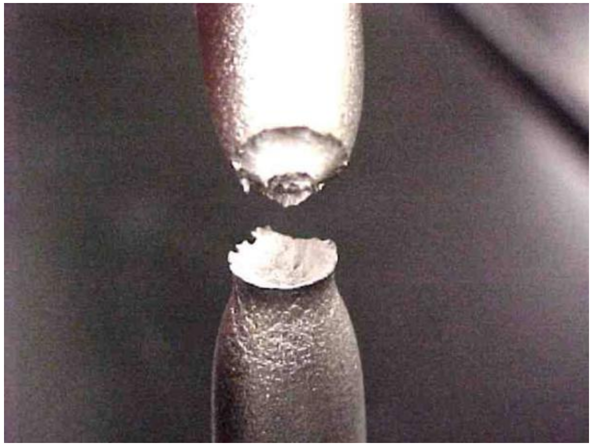
- A further increase in the load causes the specimen to thin uniformly and then to ***neck.*** After necking the specimen will break or fracture.
- When the fracture occurs one side of the specimen has a rough cone shape and the other has a rough cup shape. This is known as **a *cup and cone*** fracture

Producing graphs

Two basic graphs:

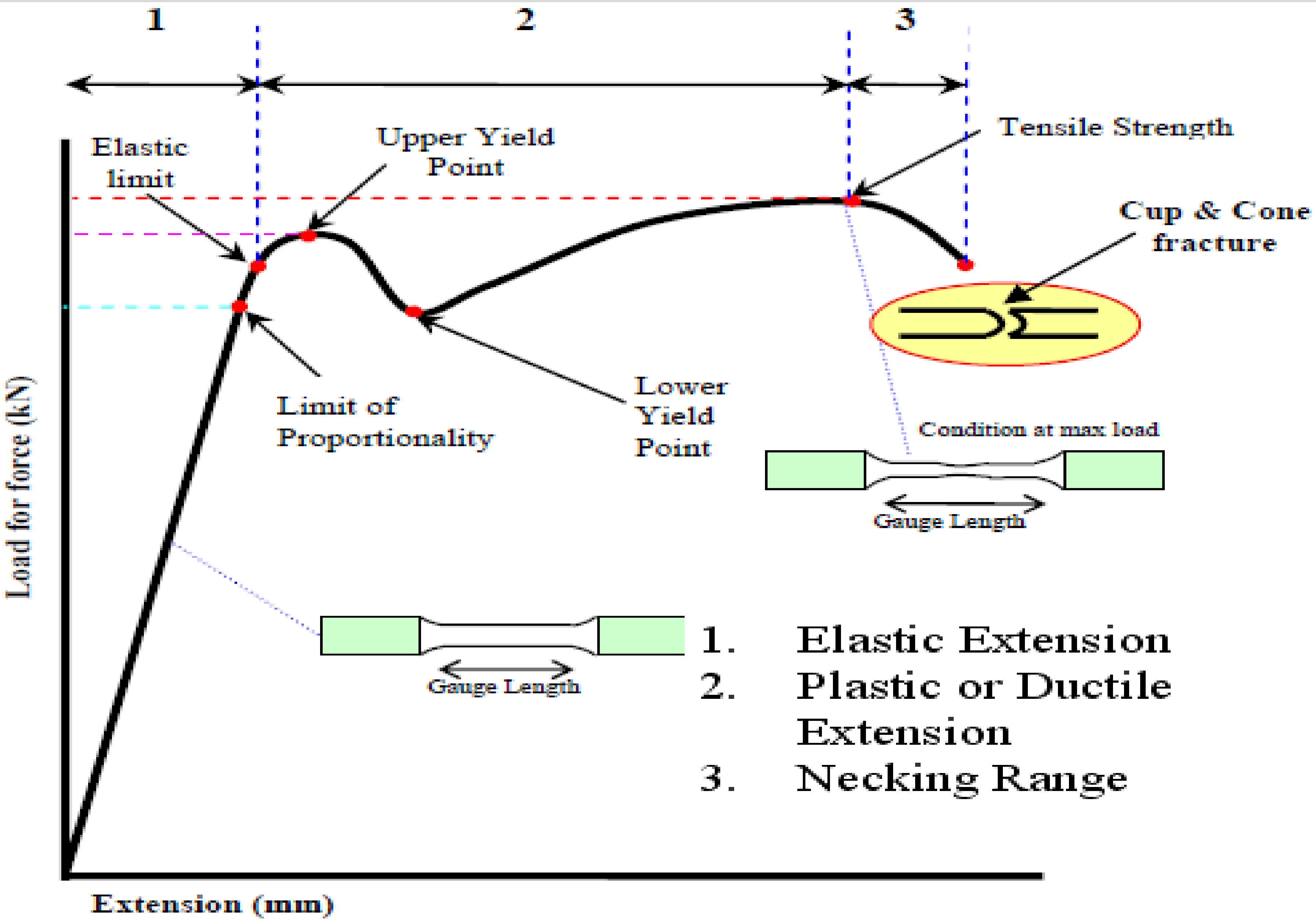
Load / extension graph.

Stress / strain graph.

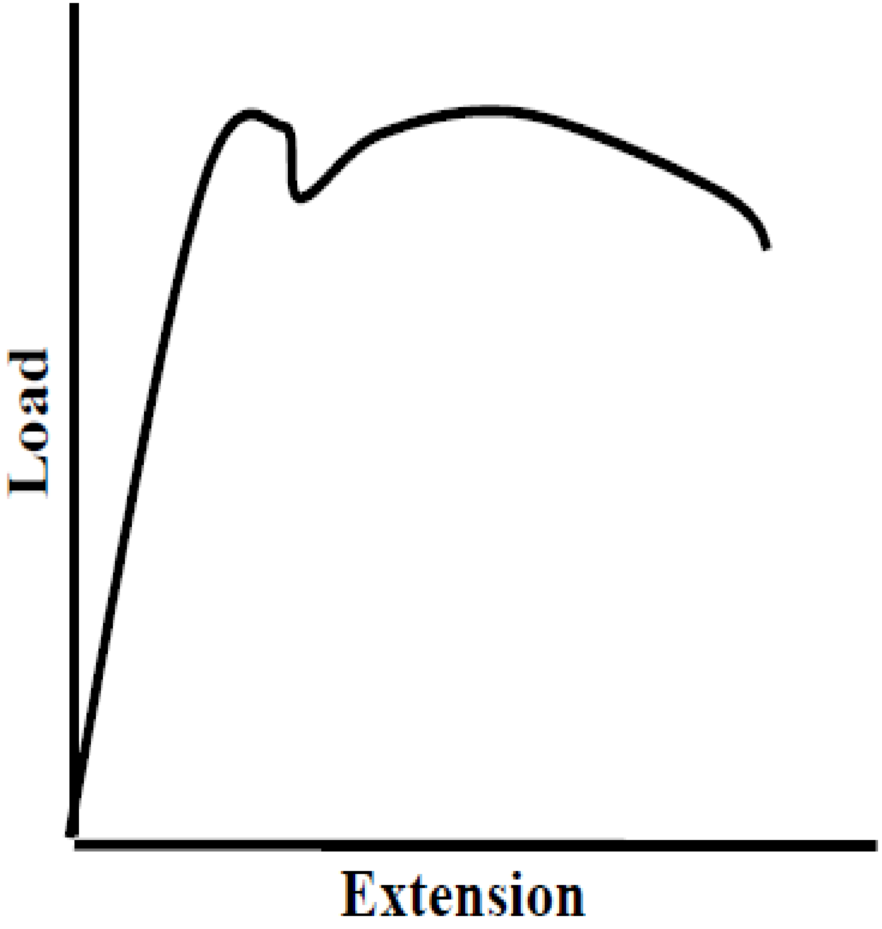


cup and cone

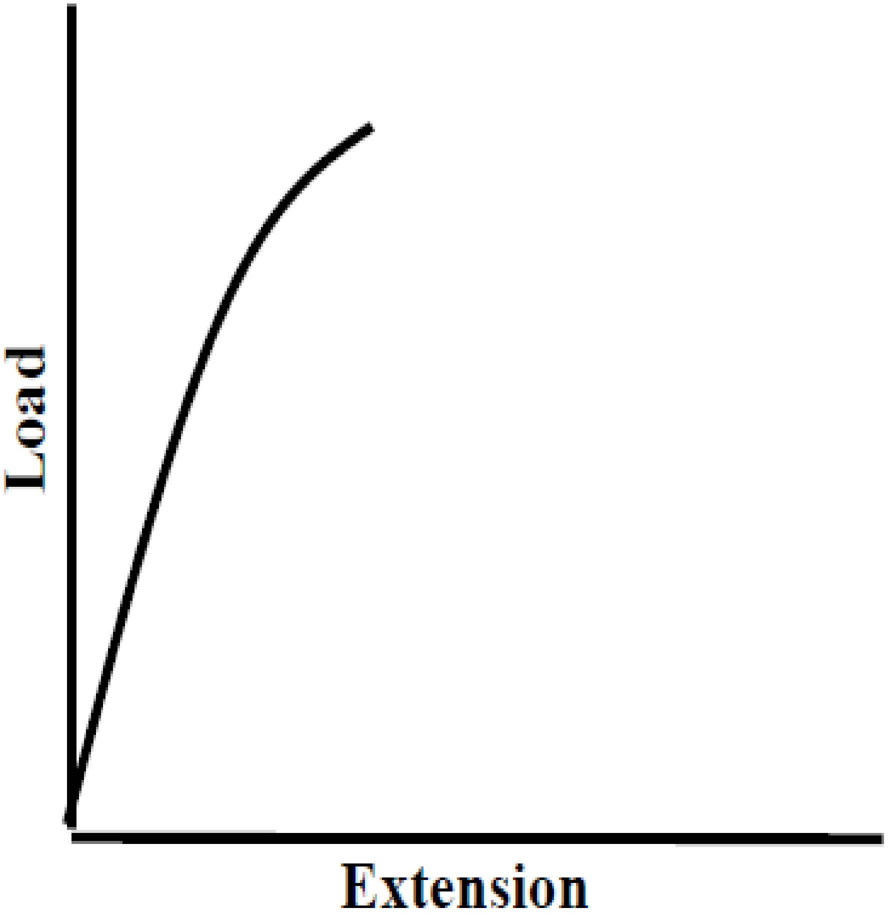
Load / extension graph.



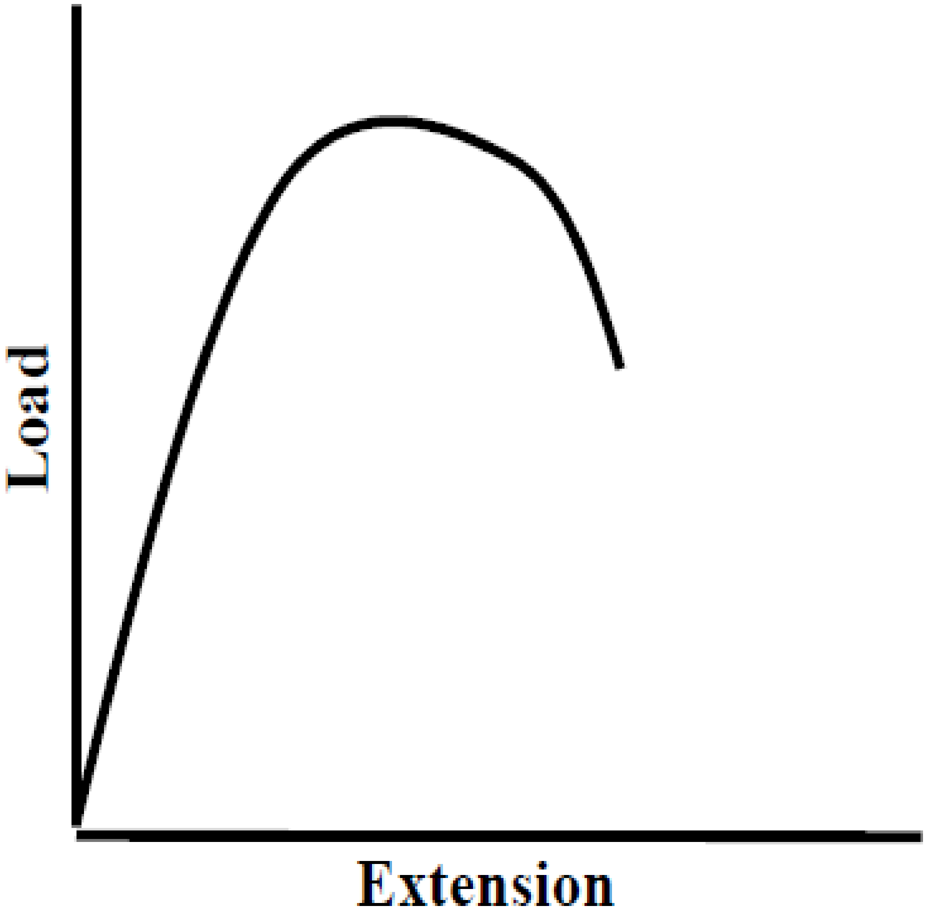
1. Elastic Extension
2. Plastic or Ductile Extension
3. Necking Range



- Good ductility
- Definite elastic limit
- Example of material – low carbon steel



- Small amounts of elasticity
- No ductility
- A brittle material
- Example of material – cast iron



- Very good ductility
- Example of material – softened brass

LINEAR ELASTIC PROPERTIES

- **Modulus of Elasticity, E (also known as Young's modulus):** the ratio of stress to strain below the elastic limit.

  - **Hooke's Law**:

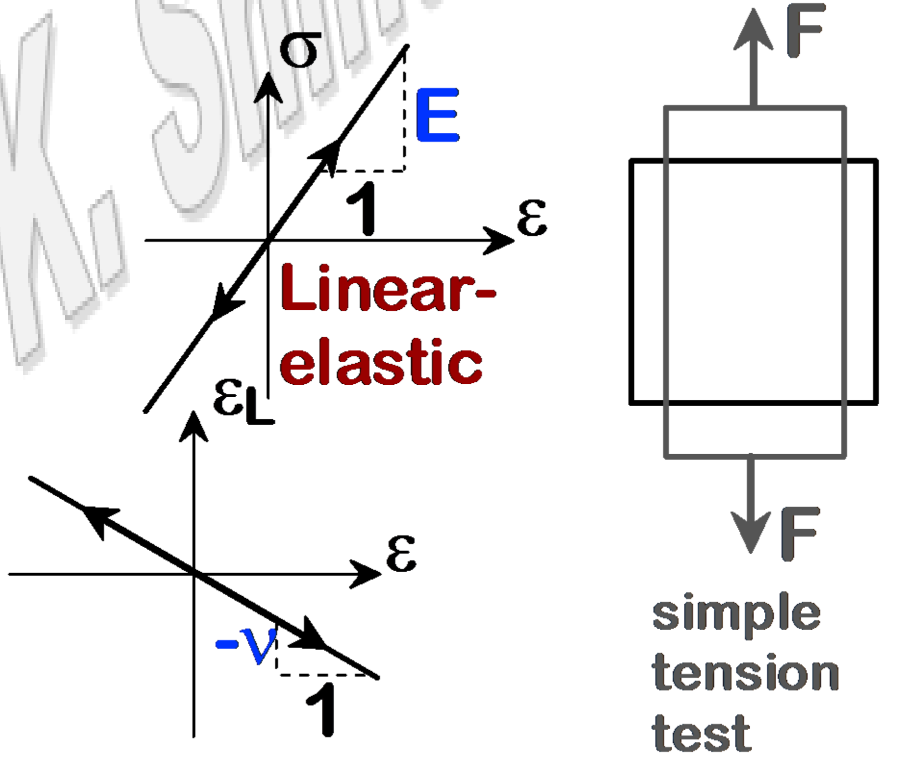
$$\sigma = E\,\varepsilon$$

  - **Poisson's ratio, ν**:

$$\nu = -\frac{\varepsilon_L}{\varepsilon}$$

metals: ν ~ 0.33
ceramics: ~0.25
polymers: ~0.40

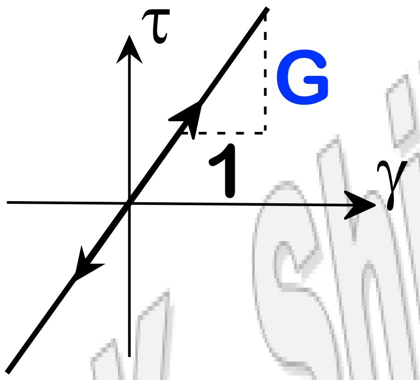
Units:
E: [GPa] or [psi]
ν: dimensionless

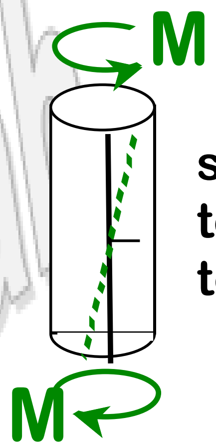


OTHER ELASTIC PROPERTIES

- **Elastic Shear modulus, G:**

$$\tau = G\gamma$$

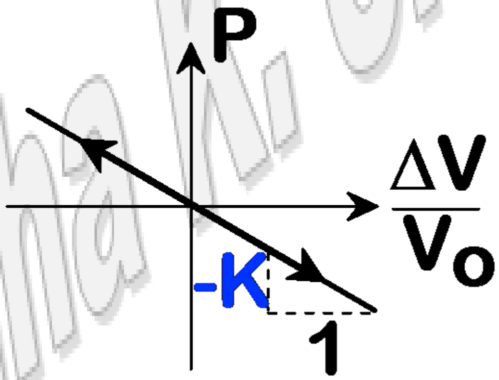


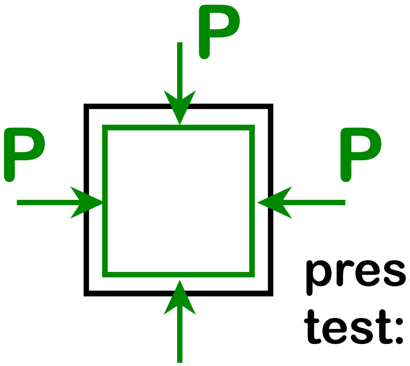


simple
torsion
test

- **Elastic Bulk modulus, K:**

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





pressure
test: Init.
vol =V_o.
Vol chg.
= ΔV

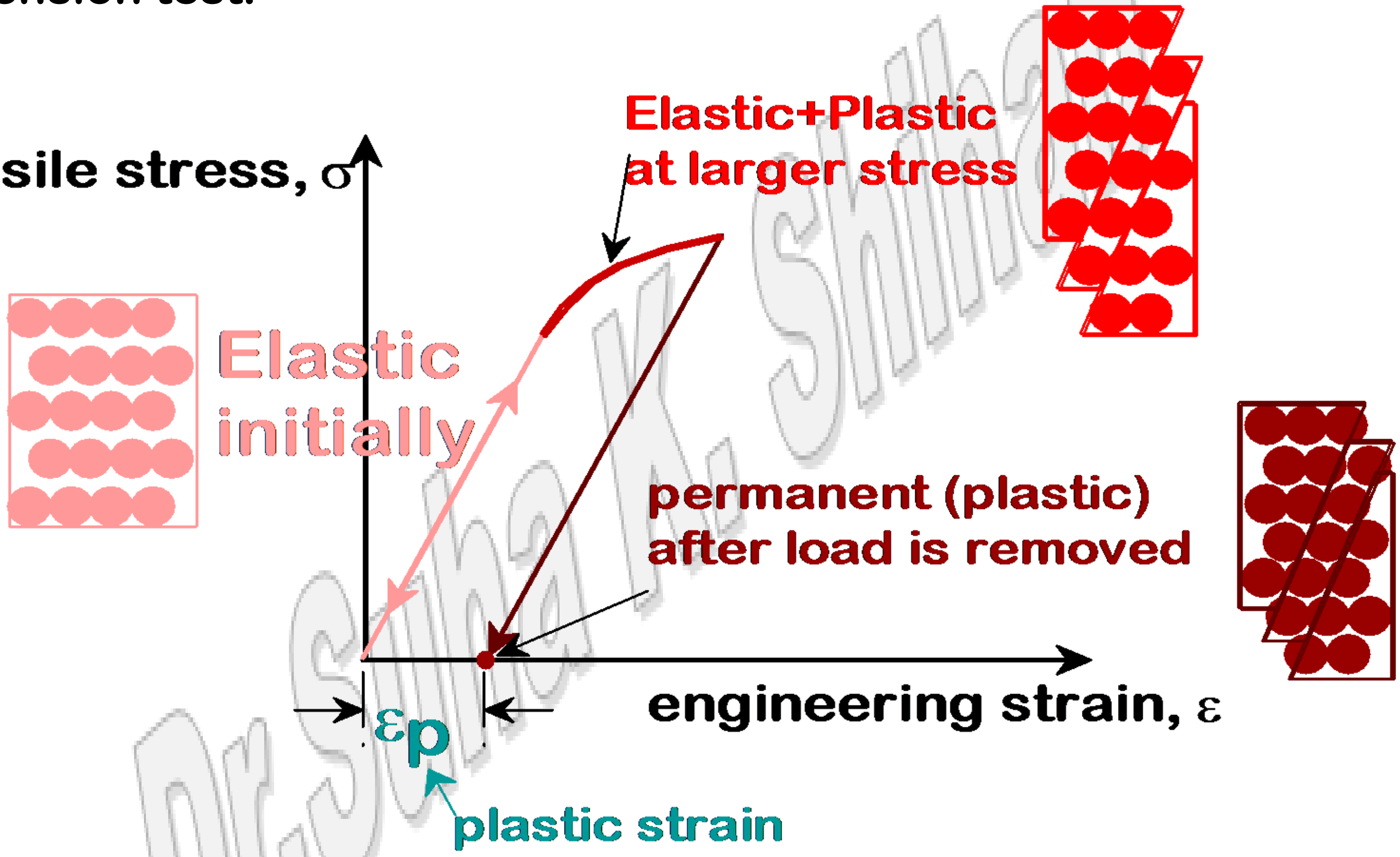
- **Special relations for isotropic materials:**

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

PLASTIC (PERMANENT) DEFORMATION

(at lower temperatures, $T < T_{melt}/3$)

- **Simple tension test:**



- **A permanent deformation (usually considered for T<Tm/3).**
- **Atoms break bonds and form new ones.**
- **In metals, plastic deformation occurs typically at strain ≥0.005.**

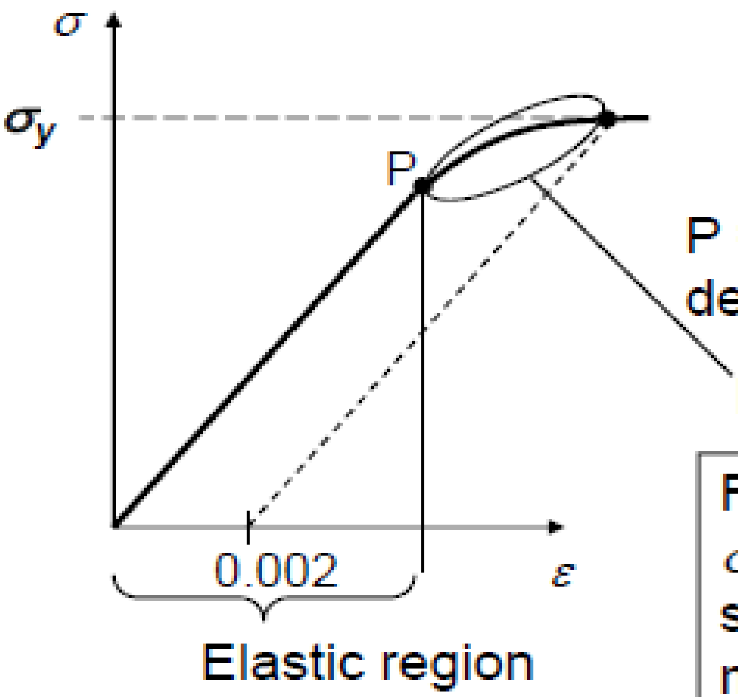
Tensile properties

A. Yield strength (σ_y): the strength required to produce a very slight yet specified amount of plastic deformation.

What is the specified amount of strain?

Strain offset method

1. Start at 0.002 strain (for most metals).
2. Draw a line parallel to the linear region.
3. σ_y = where the dotted line crosses the stress-strain curve.



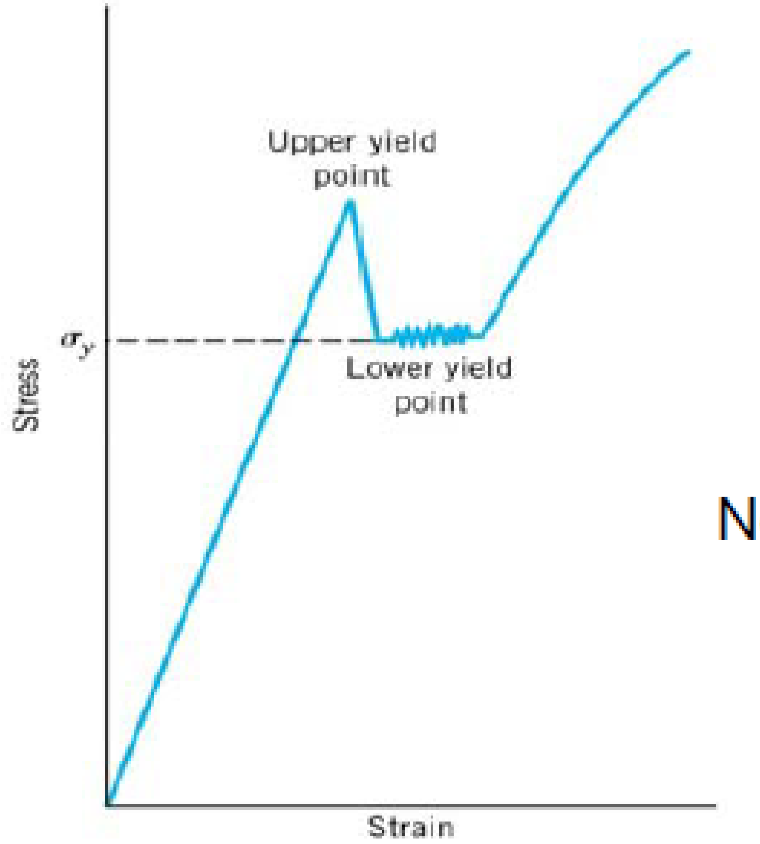
P = proportional limit (beginning of deviation from linear behavior.

Mixed elastic-plastic behavior

For materials with nonlinear elastic region: σ_y is defined as stress required to produce specific amount of strain (e.g. ~0.005 for most metals).

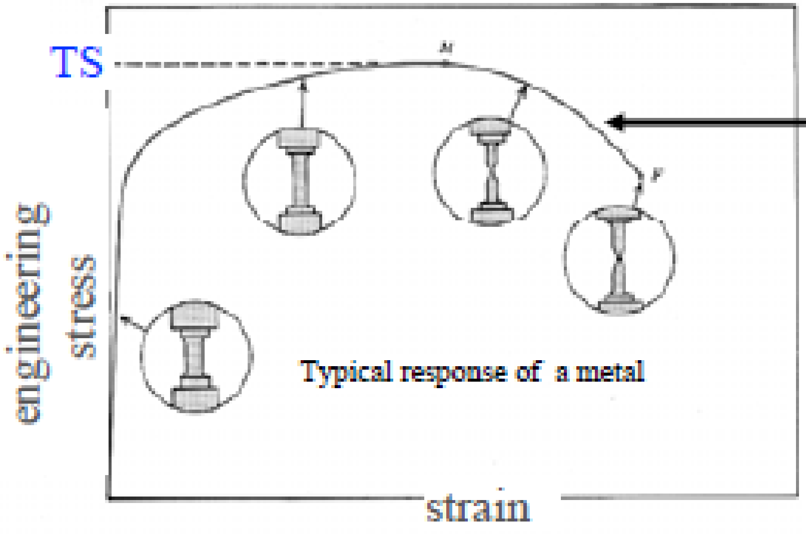
Tensile properties

Yield point phenomenon occurs when elastic-plastic transition is well-defined and abrupt.



No offset methods required here.

True stress and strain



Notice that past maximum stress point, σ decreases.

→ Does this mean that the material is becoming weaker?

Necking leads to smaller cross sectional area!

Recall: Engineering Stress = $\sigma = \dfrac{F}{A_o}$ ← Original cross sectional area!

True Stress = $\sigma_T = \dfrac{F}{A_i}$

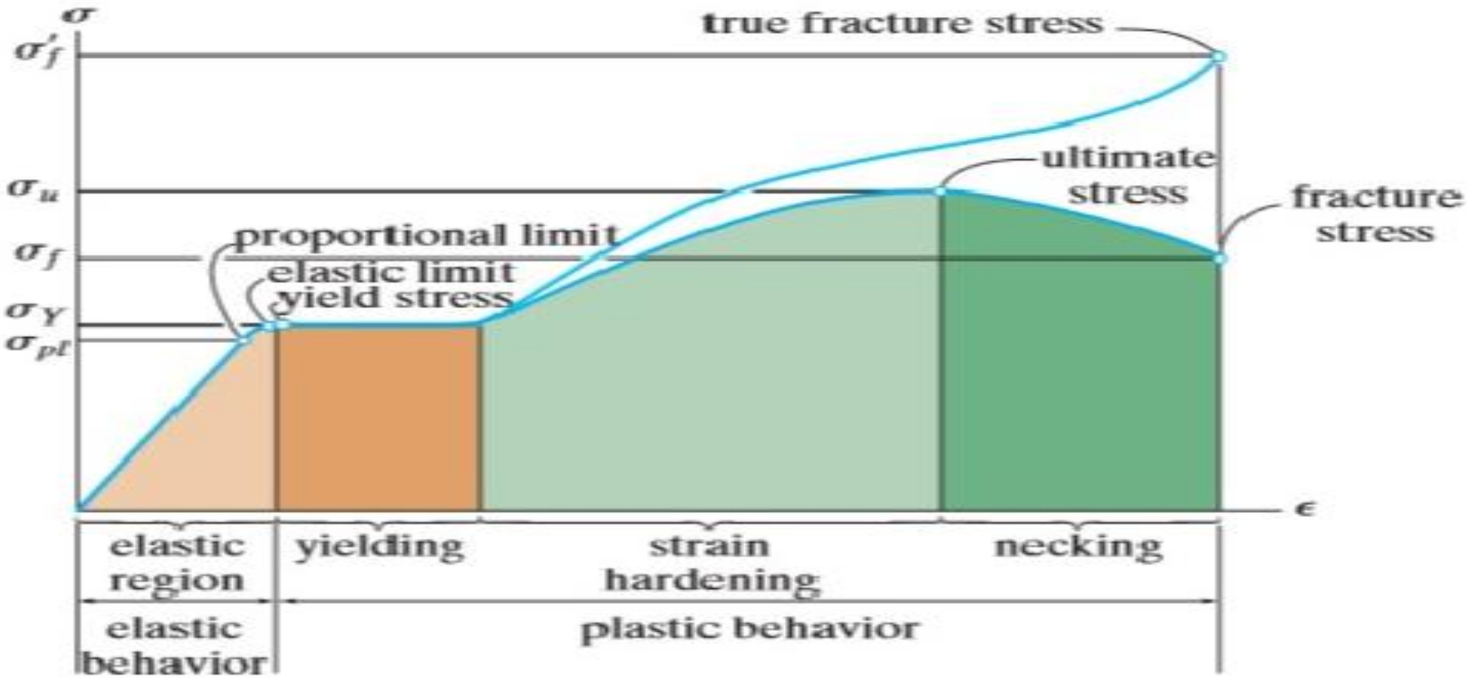
True Strain = $\varepsilon_T = \ln\dfrac{l_i}{l_o}$

A_i = instantaneous area
l_i = instantaneous length

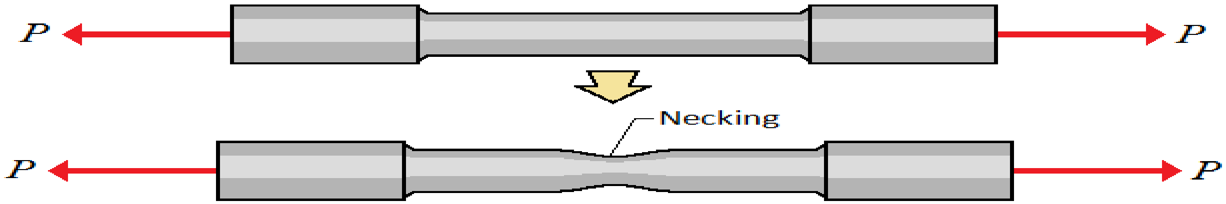
If no net volume change (i.e. $A_i\, l_i = A_o\, l_o$)

$$\left.\begin{aligned}\sigma_T &= \sigma(1+\varepsilon)\\ \varepsilon_T &= \ln(1+\varepsilon)\end{aligned}\right\}$$

Only true at the onset of necking



Conventional and true stress-strain diagrams for ductile material (steel) (not to scale)



The result of the applied force and the actual cross area at the moment of applying force on that area is called **true stress**.

Where as, the applied force divided by the initial cross section area is called as **engineering stress**.

True Stress (σ_T)

True stress is the stress determined by the instantaneous load acting on the instantaneous cross-sectional area

True stress is related to engineering stress:

Assuming material volume remains constant

$$A_o \ell_o = A \ell$$

$$\sigma_T = \frac{P}{A} = \frac{P}{A} * \frac{A_o}{A_o} = \frac{P}{A_o} * \frac{A_o}{A}$$

$$\frac{A_o}{A} = \frac{\ell}{\ell_o} = \frac{\delta + \ell_o}{\ell_o} = \frac{\delta}{\ell_o} + 1 = (1 + \varepsilon)$$

$$\sigma_T = \frac{P}{A_o}(1 + \varepsilon) = \sigma(1 + \varepsilon)$$

True Strain (ε_T)

The rate of instantaneous increase in the instantaneous gauge length.

$$\varepsilon_T = \int \frac{d\ell}{\ell} = \ln\left(\frac{\ell}{\ell_o}\right)$$

$$\varepsilon_T = \ln\left(\frac{\ell_o + \Delta\ell}{\ell_o}\right) \Rightarrow \ln\left(\frac{\ell_o}{\ell_o} + \frac{\Delta\ell}{\ell_o}\right)$$

$$\varepsilon_T = \ln(1 + \varepsilon)$$

Elastic recovery after plastic deformation

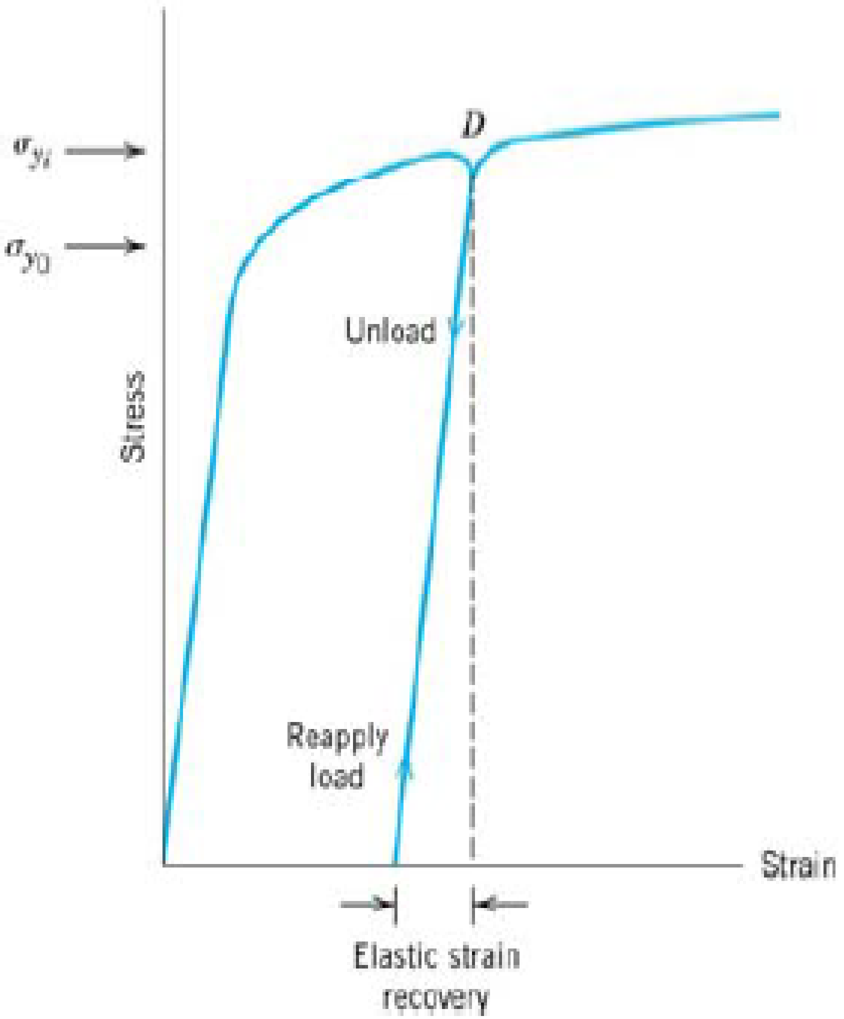


FIGURE 6.17 Schematic tensile stress–strain diagram showing the phenomena of elastic strain recovery and strain hardening. The initial yield strength is designated as σ_{y_0}; σ_{y_i} is the yield strength after releasing the load at point *D*, and then upon reloading.

This behavior is exploited to increase yield strengths of metals: **strain hardening** (also called **cold working**).

Strain Hardening parameter (n)

The most commonly used expression for strain hardening is the simple power law:

$$\sigma_T = K\varepsilon_T{}^n$$

K = strength coefficient

n = strain hardening exponent

Work hardening, also known as strain hardening or cold working: is the strengthening of a metal by plastic deformation. This strengthening occurs because of dislocation movements and dislocation generation within the crystal structure of the material. So , Strain hardening is due to the increased resistance to dislocation movement through a crystal structure.

The value of the strain hardening exponent lies between 0 and 1. A value of 0 means that a material is a perfectly **plastic** solid, while a value of 1 represents a 100% **elastic** solid. Most metals have an n value between 0.10 and 0.50

Effects of Strain Hardening

- Loss of Ductility. ☹
- Decrease in Modulus of Toughness. ☹
- Apparent increase in Yield Strength. ☺
- Ultimate Tensile Strength is unaffected.
- Modulus of Elasticity is unaffected.

Strain Hardening in Metal Processing

- **Hot-Working:**

  milling, rolling: to its final shape

- **Cold-Working:**
  A process of **strain hardening** at **room** temperature to deform the material **beyond the elastic range** to obtain a desired property.

- **Examples of cold-working:** rolling, drawing, extruding, cutting, pulling, indenting…

Purpose of Cold-Working

➢ **To make its final shape**

➢ **To alter its structure and properties:**

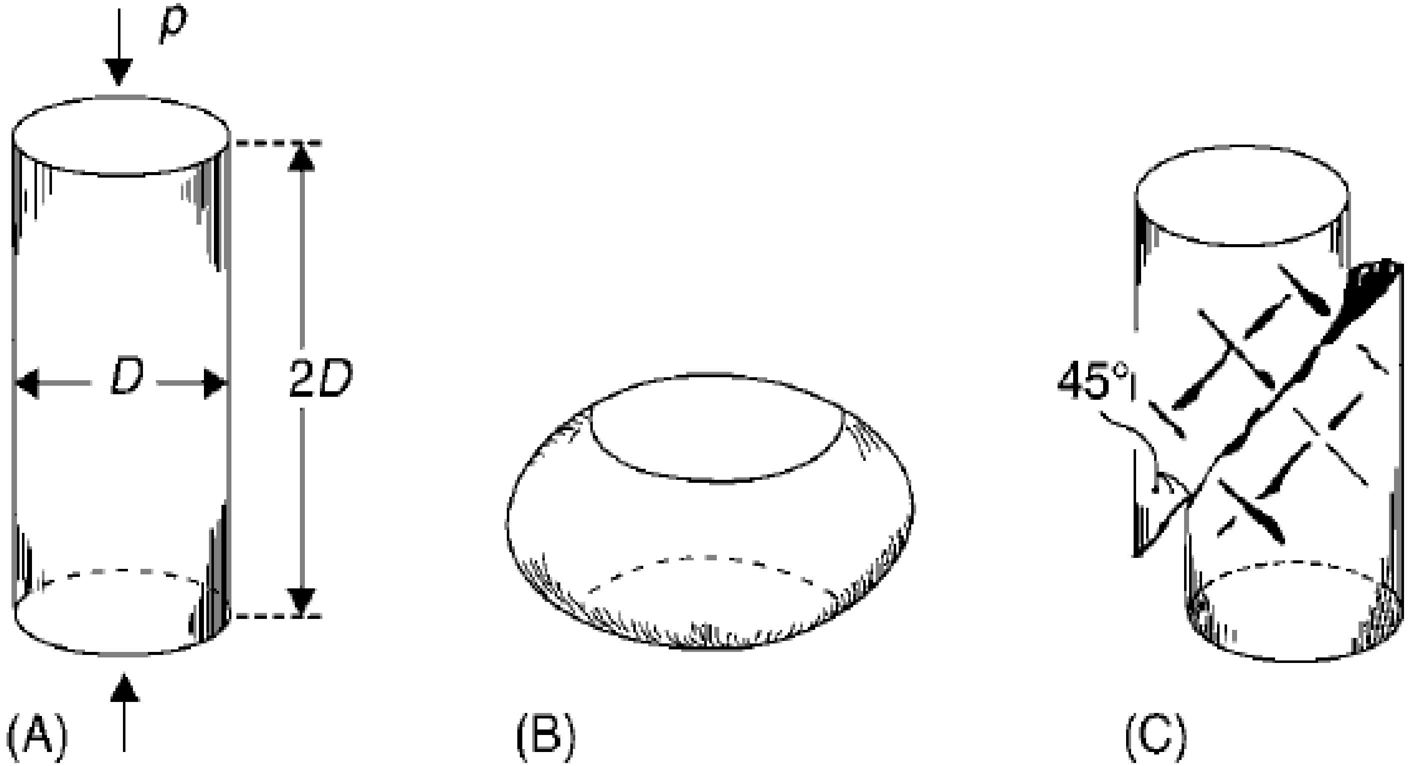
Increase yield strength ☺

Decrease ductility ☹

Compression Testing

These tests are used mainly in connection ***with cast iron and concrete***, since these are materials more likely to be used under the action of compressive forces than in tension. A cylindrical block, the length of which is twice its diameter, is used as a test-piece (Figure A). This is compressed (using a tensile-testing machine running in ‘ reverse ’) until it fails.

Malleable metals do not show a well-defined point of failure (Figure B), but with brittle materials C the ultimate compressive stress can be measured accurately, since the material fails suddenly, usually by multiple shear at angles of 45 ° to the direction of compression.



T he behaviour of brittle and ductile materials during a compression test.

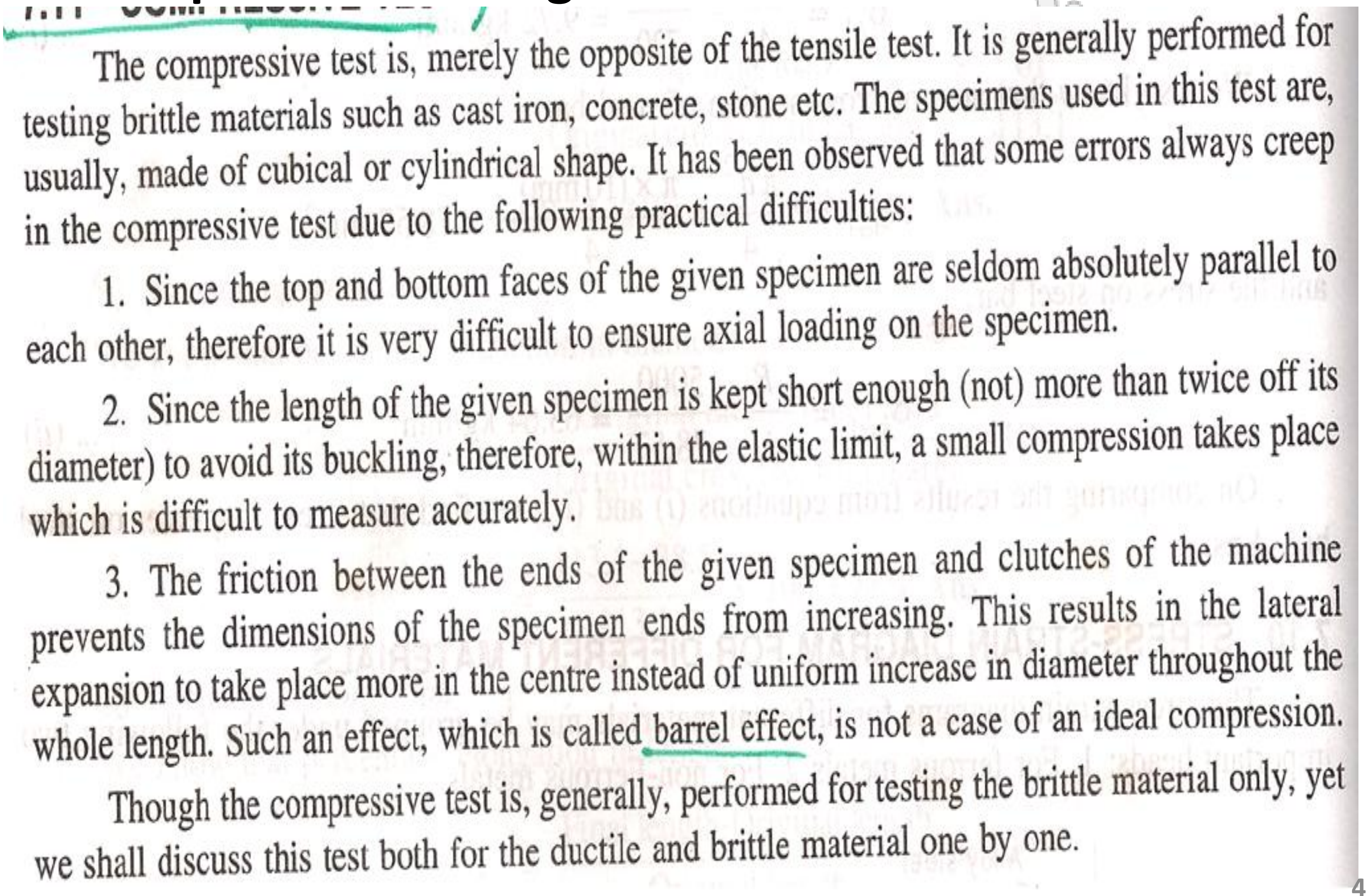
Compression Testing Machines

Many operations in manufacturing, particularly processes such as forging, rolling, and extrusion , are performed with the workpiece subjected to compressive stresses. The compression test, in which the specimen is subjected to a compressive load, gives information that is useful for estimating forces and power requirements in these processes.

For **brittle materials, the compressive strength is relatively easy to obtain, showing marked failure**. **However, for ductile materials, the compressive strength is generally based on an arbitrary deformation value.** ***Ductile materials do not exhibit the sudden fractures that brittle materials present.*** They tend to **buckle** and "**barrel out**".

Bulging of a Sample under Compressive Loads

Compression Testing



The compressive test is, merely the opposite of the tensile test. It is generally performed for testing brittle materials such as cast iron, concrete, stone etc. The specimens used in this test are, usually, made of cubical or cylindrical shape. It has been observed that some errors always creep in the compressive test due to the following practical difficulties:

1. Since the top and bottom faces of the given specimen are seldom absolutely parallel to each other, therefore it is very difficult to ensure axial loading on the specimen.
2. Since the length of the given specimen is kept short enough (not) more than twice off its diameter) to avoid its buckling, therefore, within the elastic limit, a small compression takes place which is difficult to measure accurately.
3. The friction between the ends of the given specimen and clutches of the machine prevents the dimensions of the specimen ends from increasing. This results in the lateral expansion to take place more in the centre instead of uniform increase in diameter throughout the whole length. Such an effect, which is called barrel effect, is not a case of an ideal compression.

Though the compressive test is, generally, performed for testing the brittle material only, yet we shall discuss this test both for the ductile and brittle material one by one.

Torsion test

Torsion is the twisting of an object due to an applied torque

Torsion Testing Equipment

Shear Testing Procedure

- Twisting head with chuck (one end)
- Weighing head (other end) – measures the twisting moment or torque
- Troptometer (twisting measuring device) – measures the deformation of the specimen

Torsion test

- Ratio of shear stress to the shear strain in the elastic range is called **shear modulus**, or **modulus of rigidity, G**
- G is a quantity related to the modulus of elasticity E

$$\tau = G * \gamma$$

$$G = \frac{E}{2*(1+\upsilon)}$$

Considering a cylindrical bar with one end being twisted as shown in figure 1, the twisting moment *MT is resisted by the shear stress τ existing across the specimen section. This shear stress is* zero at the center of the bar, increases linearly with its radius and finally reaches its maximum value at the peripheral of the bar. If the cylindrical bar with a length of *L, the twisting moment can be related* to the shear stress as follow

$$\frac{M_T}{J} = \frac{G\theta}{L} = \frac{\tau}{r}$$

The shear strain, γ, can be calculated from equation:

$$\gamma = \tan\theta = \frac{r\theta}{L}$$

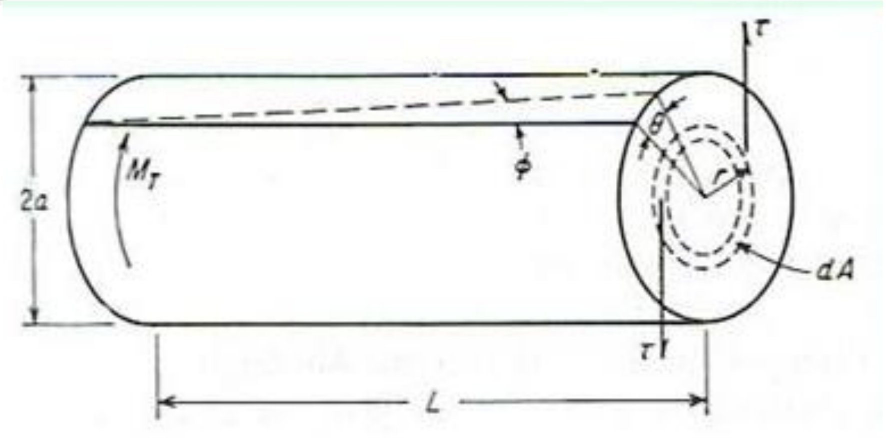


Figure1 : Torsion of a solid bar

M_T = torsional moment, Nm

J is the polar moment of inertia, mm^4 or in^4

G is the shear modulus, N/mm^2 or lbf/in^2

θ is degree of rotation, radian

r is the radius of the cylindrical bar, mm or in

L is the length of the cylindrical bar, mm or in

τ is the shear stress, N/mm^2 or lbf/in^2

Within the elastic range of deformation, the shear stress can be calculated according to equation:

$$\tau = \frac{M_T r}{J}$$

For **a solid cylindrical specimen**, the polar moment ***$J = \pi D^4/32$**, we can therefore* ress as shown in equation:

$$\tau = \frac{M_T D/2}{\pi D^4/32} = \frac{16 M_T}{\pi D^3}$$

General types of Current hardness testing…..

Current practice divides hardness testing into three categories:

- **Macrohardness**:

  Refers to testing with applied loads on the indenter of more than 1 kg and material being tested are tools, dies and sheet material in the heavier gages(in large scale)

- **Microhardness**:

  Refers to testing with applied loads are 1 kg or below, and material being tested is very thin (down to 0.0125 mm or 0.0005 inch).

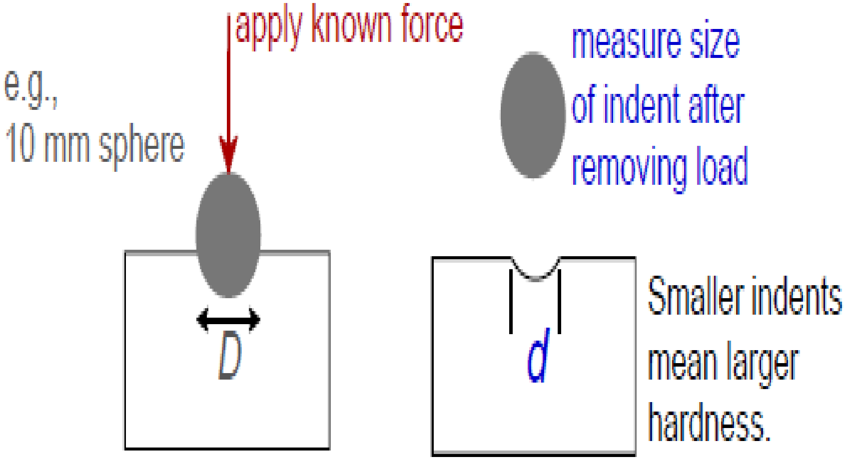
- **Nanohardness:**

  Tests measure hardness by using indenter, on the order of nano scale.

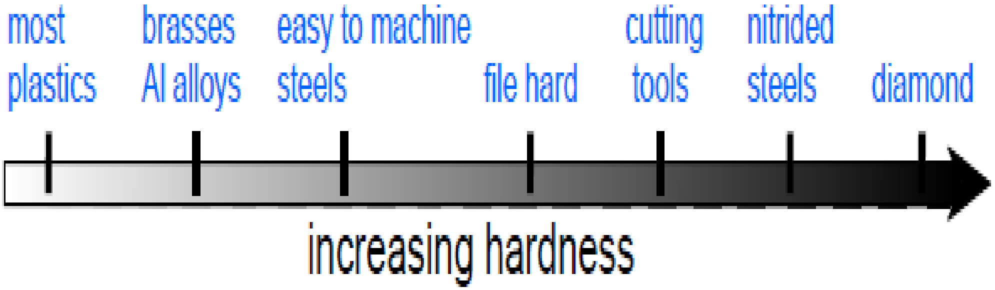
  These tests are based one new technology that allows precise measurement and control of the indenting forces and precise measurement of the indentation depth.

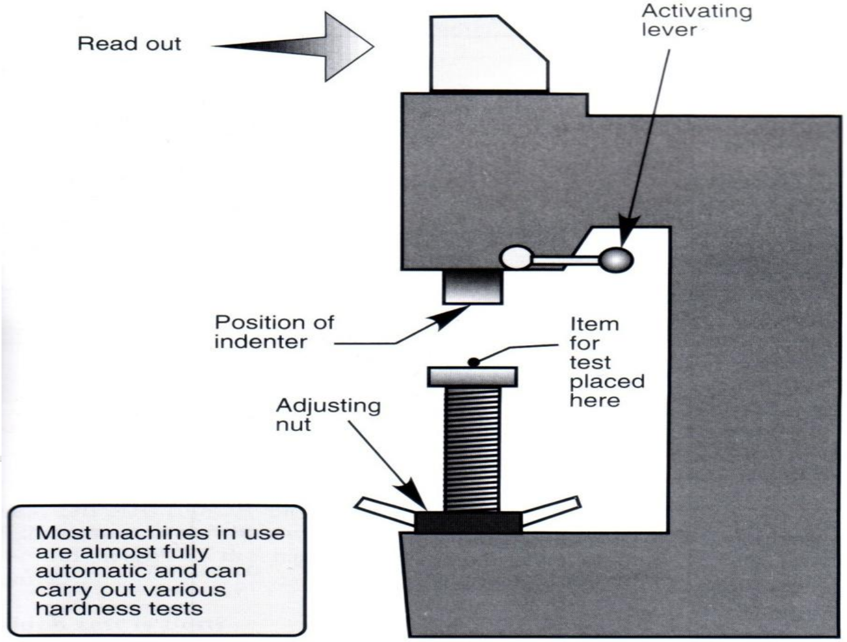
Hardness test procedure

- The indenter is pressed into the metal
- Softer materials leave a deeper indentation



Smaller indents mean larger hardness.



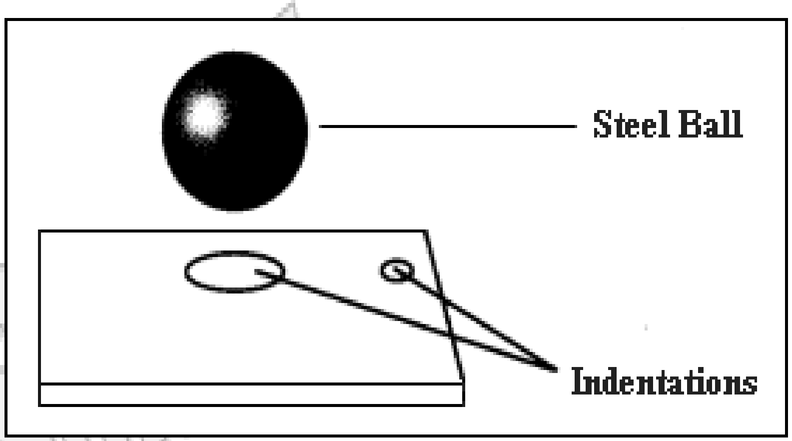


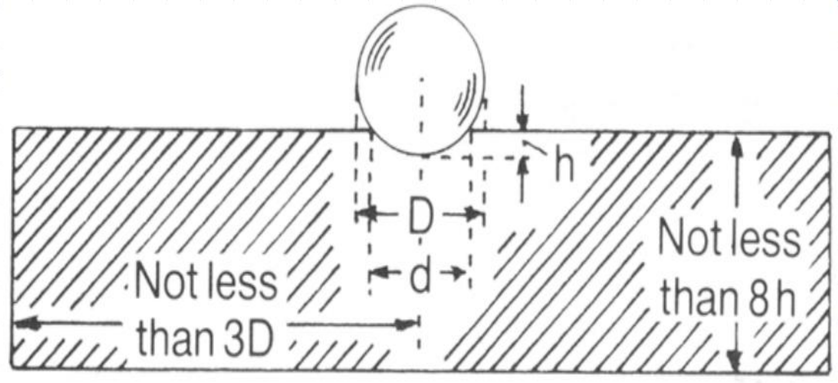
Most machines in use are almost fully automatic and can carry out various hardness tests

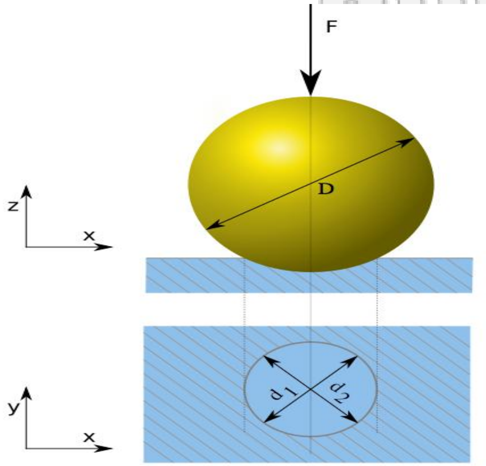
Brinell Hardness Test (BH)

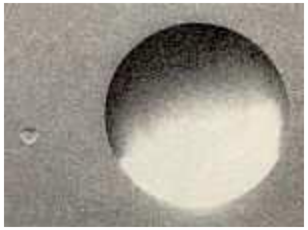
Introduction:

A Swedish, J.A.Brinell, announced Brinell hardness test. He pressed an indenter with a hard ball to the surface of a metal. During testing period, the weights were maintained constant in indicated time. A low-order microscope measured the diameters of indentations. The values of diameters will be transferred respectively into the value of Brinell hardness, HB value.









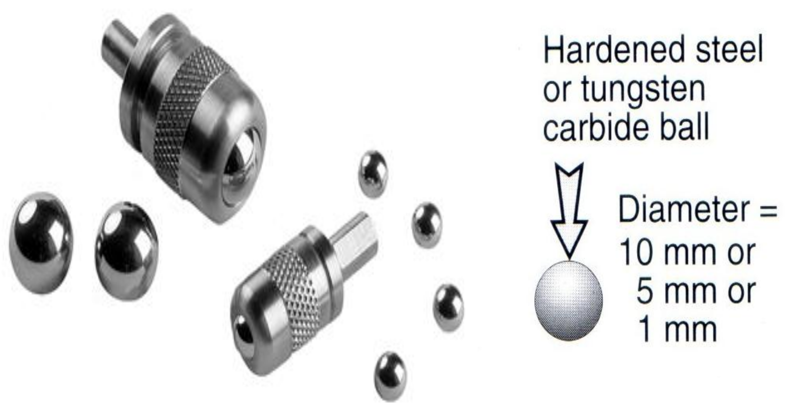
Brinell hardness impression

- The test be made with a ball of 10 mm diameter under a load of 3,000 kg for ferrous metals the loaded ball is pressed into the specimen for at least 10s.
- But for non-ferrous these parameter are different in which load of 500 kgf is applied for 30s.
- The diameter of the impression produced is measured by means of a microscope containing an ocular scale, usually graduated in tenths of a millimeter, permitting estimate to the nearest 0.05 mm.

$$HB = \frac{2P}{\pi D(D-\sqrt{(D^2-d^2)})}$$

- P= Load placed on ball, usually 3000 kg , but 1500 kg, and 500 kg can also be used.
- D = Diameter of steel ball (= 10 mm)
- d = diameter of dent, measured by looking through a Brinell microscope.

1 kgf = 9.8N



What the meaning 250HB10/3000 ?
HB Brinell hardness, 250 the value of hardness , 10 is the ball diameter, 3000 is the force to apply (in kgf)

Rockwell Hardness

Introduction:

S.P. Rockwell announced hardness test in 1919. In the United States; however, it was used to practical by C.H. Wilson.

Different weights composed of different material indenters will inspire various usages. There are two kinds of indenters, one is with **a steel head** and the other is with **a diamond head**. Rockwell hardness test is the most popular hardness test nowadays.

Types of Rockwell testing

- **Rockwell regular testing:**

In Rockwell regular testing the minor load is 10 kg and major load (60, 100, or 150 kg) is used regardless of the type of indenter.

- **Rockwell superficial testing:**

In Rockwell superficial testing minor load is 3 kg and major loads (15, 30 or 45 kg) are used.

Test Procedure

1. Apply a minor load of 10 kg.
2. Then the dial is set to zero .
3. Then apply major load 60 to 150 kg according to the scale used for 4 to 5 seconds.
4. Release the major load only.
5. Machine will show the Rockwell Hardness Number HR on the machine.
6. All these operation will be done by machine automatically.
7. 100 number means most hard and 0 means least hard

- A = diamond, B = 1/16 in. ball, C = diamond

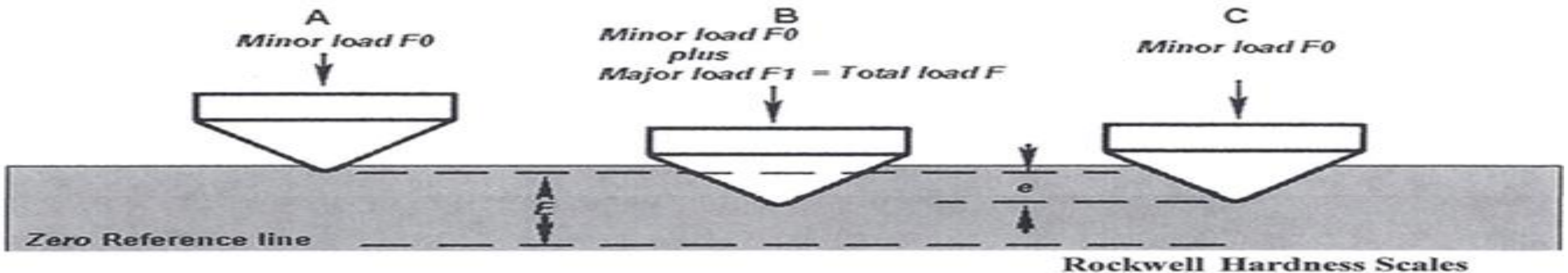


Figure: Tip Panetration

- ➢F0 = preliminary minor load in kgf
- ➢ F1 = additional major load in kgf
- ➢F = total load in kgf

Types of indenters used are :

- Rockwell B (ball) used for soft materials.
- Rockwell C (cone) uses diamond cone for hard materials.

The Rockwell hardness number is given by:

Rockwell hardness = *E – h*

E is a constant determined by the form of the indentor; for diamond cone indentor *E is 100, for a steel ball 130*

h is the penetration depth

Vickers hardness test

Introduction:

The Vickers (HV) test was developed in England is 1925 and was formally known as the Diamond Pyramid Hardness (DPH) test.

- Uses square shaped pyramid indentor.
- The Vickers test has two distinct force ranges, micro (10g to 1000g) and macro (1kg to 100kg), to cover all testing requirements.
- Measures length of diagonal on indentation.

Vickers Hardness = P/A

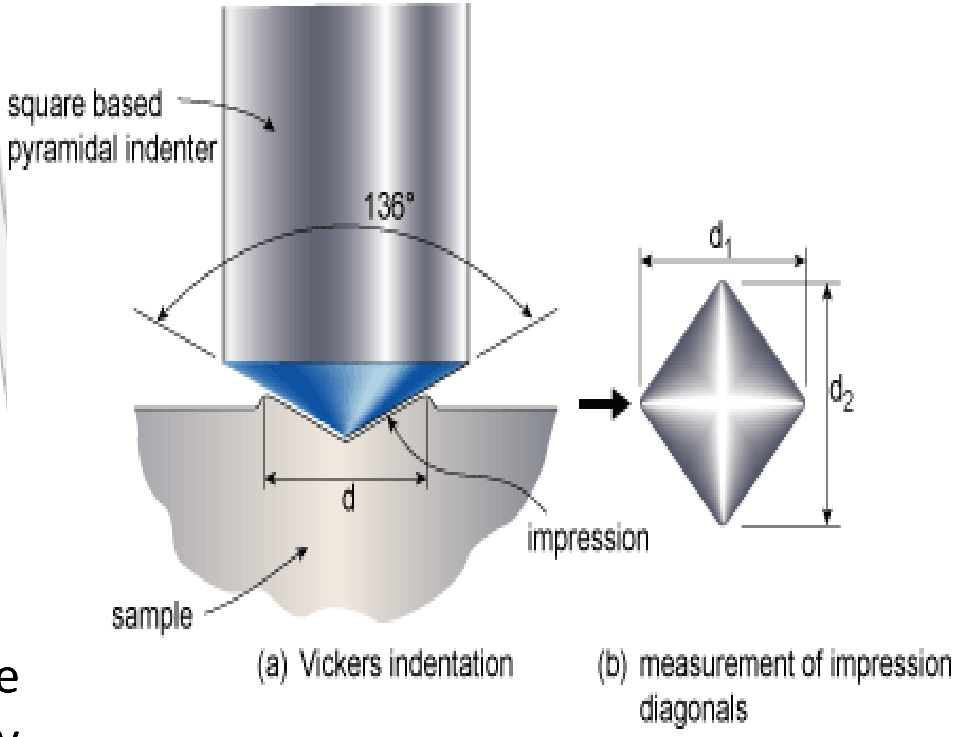
$$HV = 2P\sin(\theta/2)/L^2 = 1.8544P/L^2$$

P = load, kgf

L = mean diagonal of impression, mm

θ = face angle of diamond = 136°

$$\boxed{HV = 1.8544P/L^2}$$



(a) Vickers indentation (b) measurement of impression diagonals

Figure :*The Vickers pyramid hardness test,*

Applications

Because of the wide test force range, the Vickers test can be used on almost any metallic material. The part size is only limited by the testing instrument's capacity.

Vickers Hardness Test Procedure

1. The indenter is pressed into the sample by an accurately controlled test force.
2. The force is maintained for a specific dwell time, normally 10 – 15 seconds.
3. After the dwell time is complete, the indenter is removed leaving an indent in the sample that appears square shaped on the surface.
4. The size of the indent is determined optically by measuring the two diagonals of the square indent.
5. The Vickers hardness number is a function of the test force divided by the surface area of the indent.

Example: 375 HV_{300} means that a 300 gf load produced a Vickers hardness of 375 kgf / mm^2.

Knoop Hardness Test

Knoop (HK) hardness was developed by at the National Bureau of Standards (now NIST) in 1939.

The indenter used is a rhombic based

pyramidal diamond that produces an elongated diamond shaped indent. ***Knoop tests are mainly done at test forces from 10g to 1000g, so a high powered microscope is necessary to measure the indent size. Because of this, Knoop tests have mainly been known as microhardness tests.*** The newer standards more accurately use the term micro indentation tests. The magnifications required to measure Knoop indents dictate a highly polished test surface. To achieve this surface, the samples are normally mounted and metallurgically polished, therefore Knoop is almost always a destructive test.

Bend or flexure testing

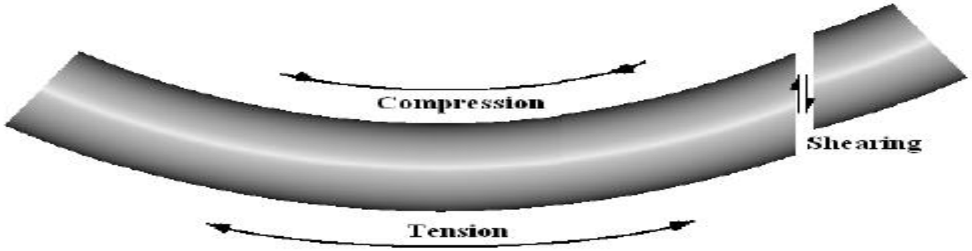
Bend or flexure testing is common in springs and brittle materials whose failure behaviours are linear such as composites, concrete, and ceramics. **Because** these materials have a very low ductility they will break before any permanent deformation of the sample occurs allowing for the accurate measurement of the flexural modulus and strength.

Why Perform a Flexure Test?

The most common purpose of a **flexure test** is to measure **flexural strength** , **flexural modulus (modulus of elasticity in bending), flexural strain and the flexural stress-strain response of the material**.

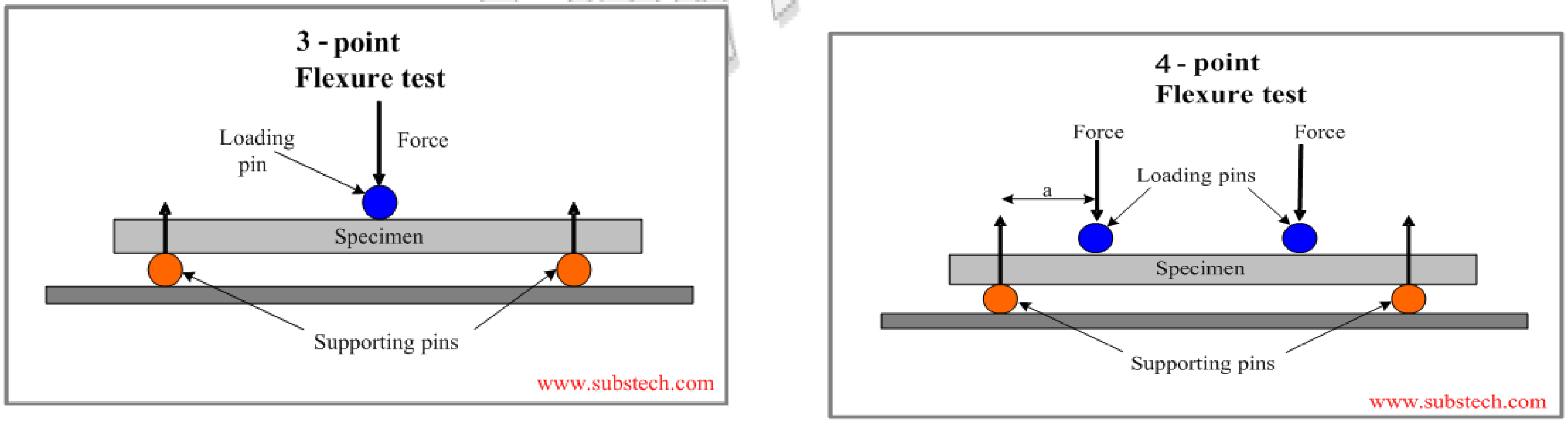
Flexural strength: is the maximum stress required to fracture a specimen in a bend test.

Flexural modulus : is calculated from the slope of the stress vs. strain deflection curve. Flexural modulus is used as an indication of a material's stiffness when flexed.



Types of Flexure Test

The two most common **types of flexure test are three point and four point flexure bending tests**. A three point bend test consists of the sample placed horizontally upon two points and the force applied to the top of the sample through a single point so that the sample is bent in the shape of a "V". A four point bend test is roughly the same except that instead of the force applied through a single point on top it is applied through two points so that the sample experiences contact at four different points and is bent more in the shape of a "U". The three point flexure test is ideal for the testing of a specific location of the sample, whereas, the four point flexure test is more suited towards the testing of a large section of the sample, which highlights the defects of the sample better than a 3-point bending test. bend testing under **three-point** or **four-point bend** arrangements as shown in figure 1 a) and b) respectively



a figure 1 b

3-point bend test

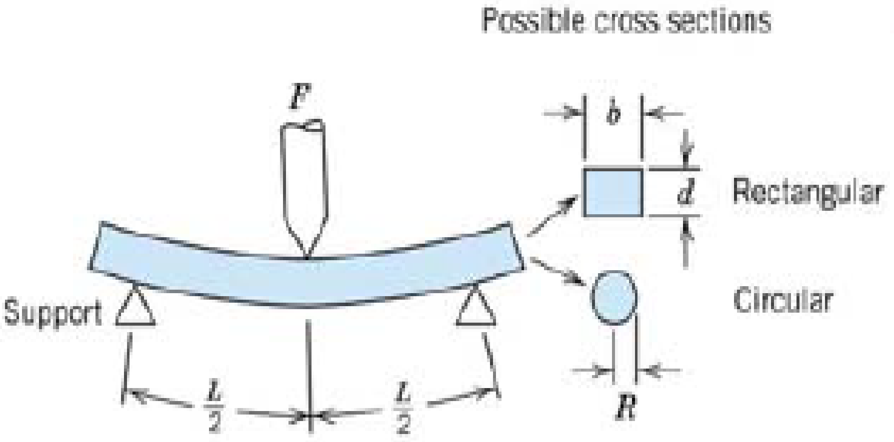


Figure 12.29 A three-point loading scheme for measuring the stress–strain behavior and flexural strength of brittle ceramics, including expressions for computing stress for rectangular and circular cross sections.

$\sigma = \text{stress} = \frac{Mc}{I}$

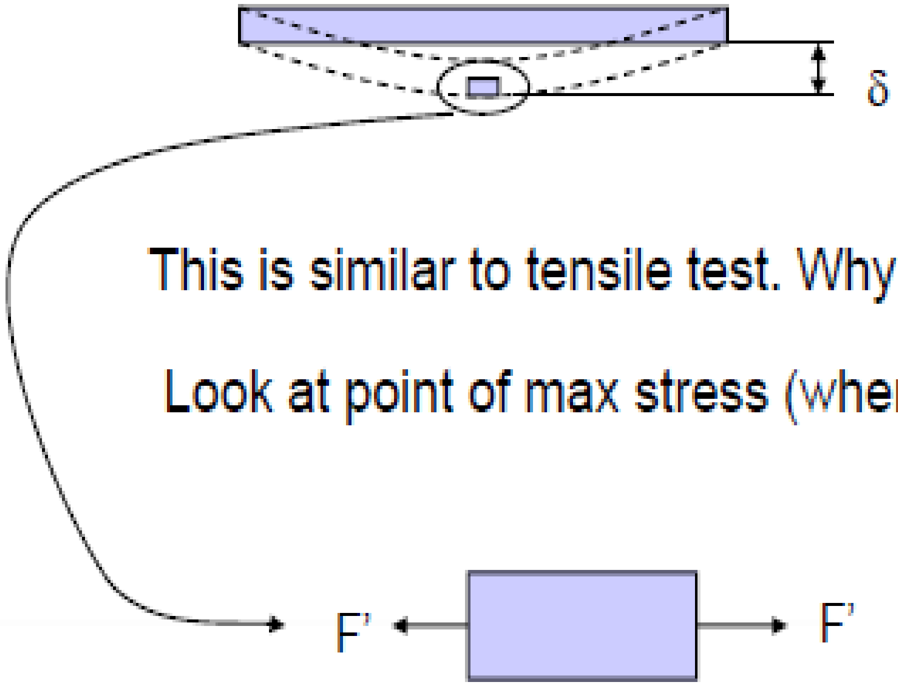
where M = maximum bending moment

c = distance from center of specimen to outer fibers

I = moment of inertia of cross section

F = applied load

	M	c	I	σ
Rectangular	$\frac{FL}{4}$	$\frac{d}{2}$	$\frac{bd^3}{12}$	$\frac{3FL}{2bd^2}$
Circular	$\frac{FL}{4}$	R	$\frac{\pi R^4}{4}$	$\frac{FL}{\pi R^3}$



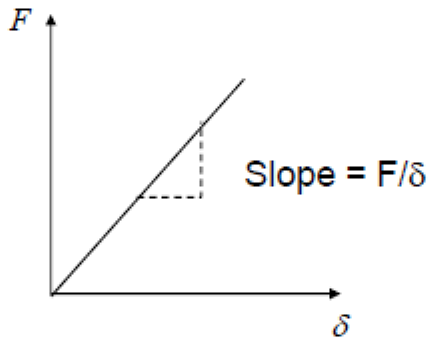
This is similar to tensile test. Why?

Look at point of max stress (where is it?).

Modulus of rupture (**Flexural strength)** = σ_{max} = $\dfrac{M_{max}\ C}{4}$

Modulus of elasticity (**Flexural modulus)** E = $\dfrac{FL^3}{48\ \delta\ J}$

Elastic modulus is proportional to F/δ

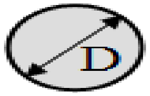
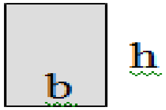


Calculation of the flexural strain

$$\varepsilon = \frac{6D\ \delta}{L^2}$$

D= Depth or thickness of tested beam, (mm)

δ = maximum deflection of the center of the beam, (mm)

	Area (A)	C	Moment of inertia J
	$\pi/4\ D^2$	$\frac{D}{2}$	$\pi/64\ D^4$
	$\pi/4(\ D^2-d^2)$	$\frac{D}{2}$	$\pi/64\ (D^4 - d^4)$
	bh	$\frac{h}{2}$	$\frac{bh^3}{12}$

Impact Test

Fracture : defined as the mechanical separation of a solid owing to the application of stress.

Fracture toughness : is a property which describes the ability of a material containing a crack to resist **fracture**, and is one of the most important properties of any material for many design applications. In addition, it is an indication of the amount of stress required to propagate a pre-existing flaw. It is a very important material property since the occurrence of flaws is not completely avoidable in the processing, fabrication, or service of a material/component. Flaws may appear as cracks, voids, metallurgical inclusions, weld defects, design discontinuities, or some combination thereof

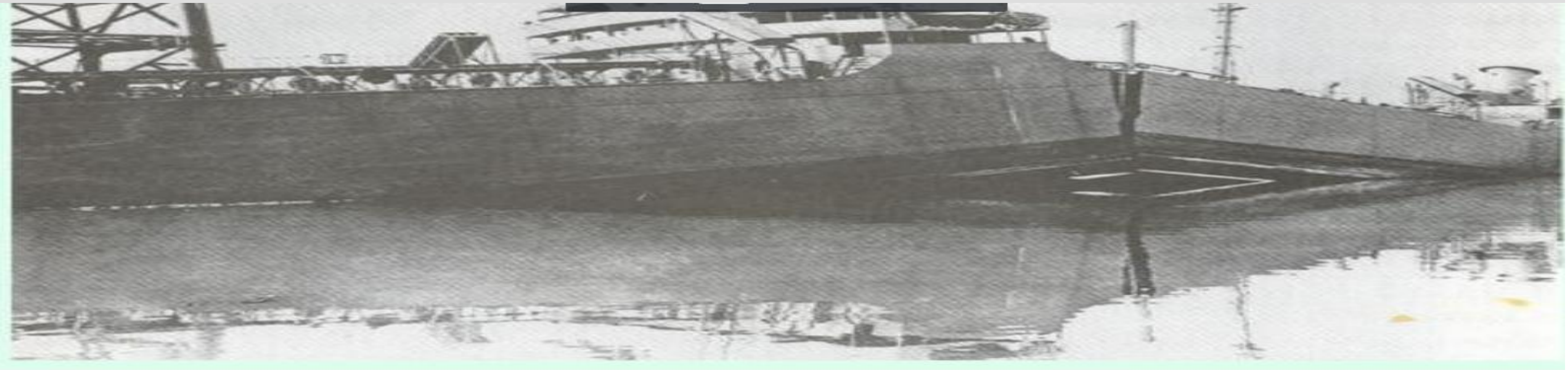
Fracture behavior depends on many external factors:

- **Strain rate**
- **Temperature**
- **Stress rate**

Types of Fracture

1. Ductile fracture
2. Brittle fracture
3. Inter-crystalline
4. Fatigue fracture

- Brittle fracture is of concern in tools designed for use at low temperatures. For example, the Royal Mail Ship "Titanic" in the Atlantic Ocean in 1912 during its sailing is attributed to the brittle failure of the hull at the very low temperatures of the seawater facing in the ocean (−2°C).
- The fracture of a large number of car axles in Alaska during the winter of 1988–1989 was attributed to the severe weather conditions.



There are three main factors of brittle fracture in materials:

1. High strain rate, that is, rapid rate of deformation
2. Stress concentration
3. Triaxial stress state, which may be introduced by the presence of a notch

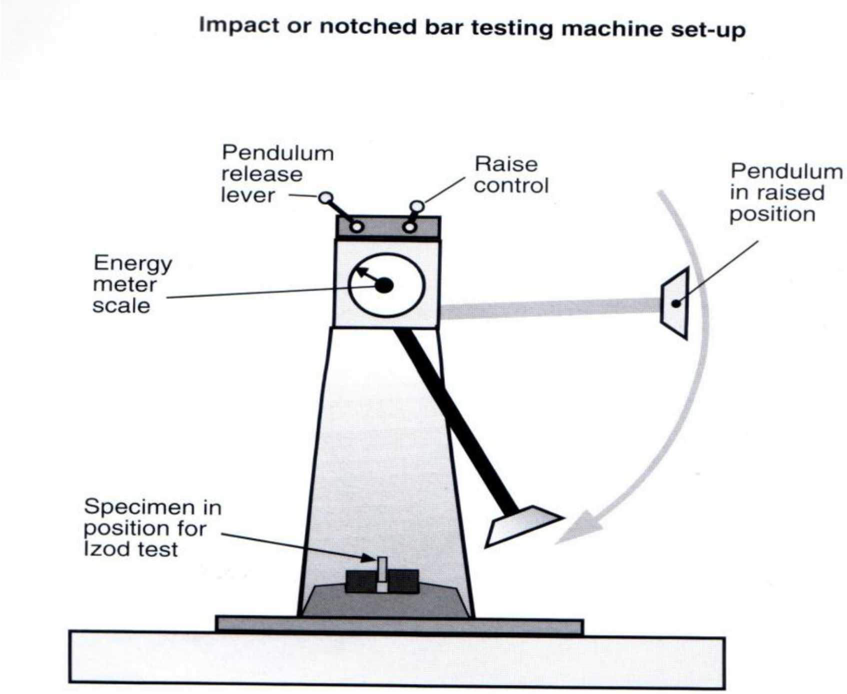
- Brittle fracture has then been investigated in great details whereas ductile fracture was however studied in a lower extent due to its less deleterious effects . Since brittle fracture has been one of the most catastrophic types leading to losses of life and cost, study of brittle fracture especially in steels has therefore been on the main focus.

Impact tests are used to indicate the toughness of a material, and particularly its capacity for resisting mechanical shock. it is used to evaluate the fracture behavior materials

In an impact test, a notched specimen is fractured by an impact blow, and the energy absorbed during the fracture is measured.

After breaking the test bar, the pendulum rebounds to a height which decreases as the energy absorbed in fracture increases.

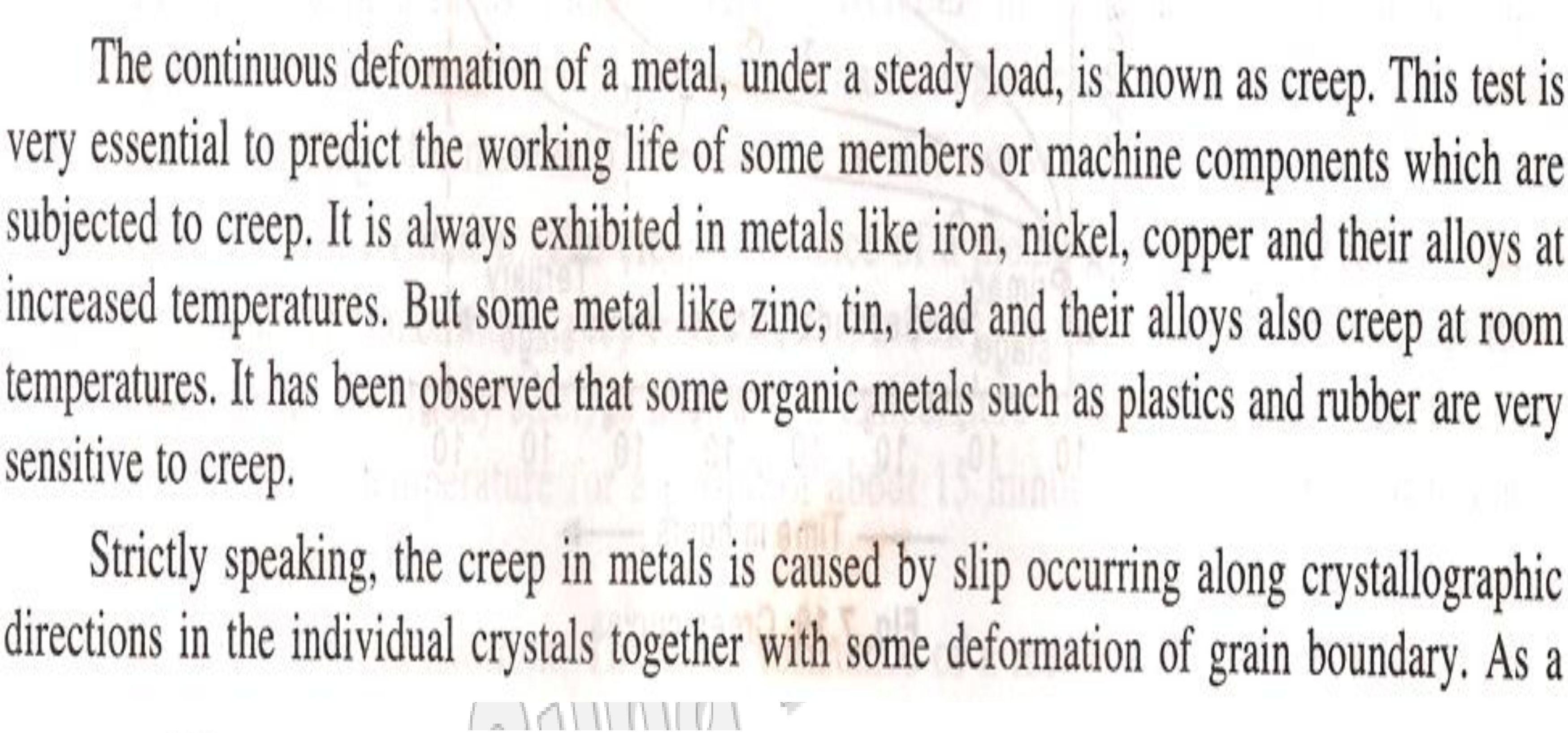
The energy absorbed in fracture, usually expressed in joules, is reading directly from a calibrated dial on the impact tester.



Toughness : is defined as the ability of a material to absorb energy.

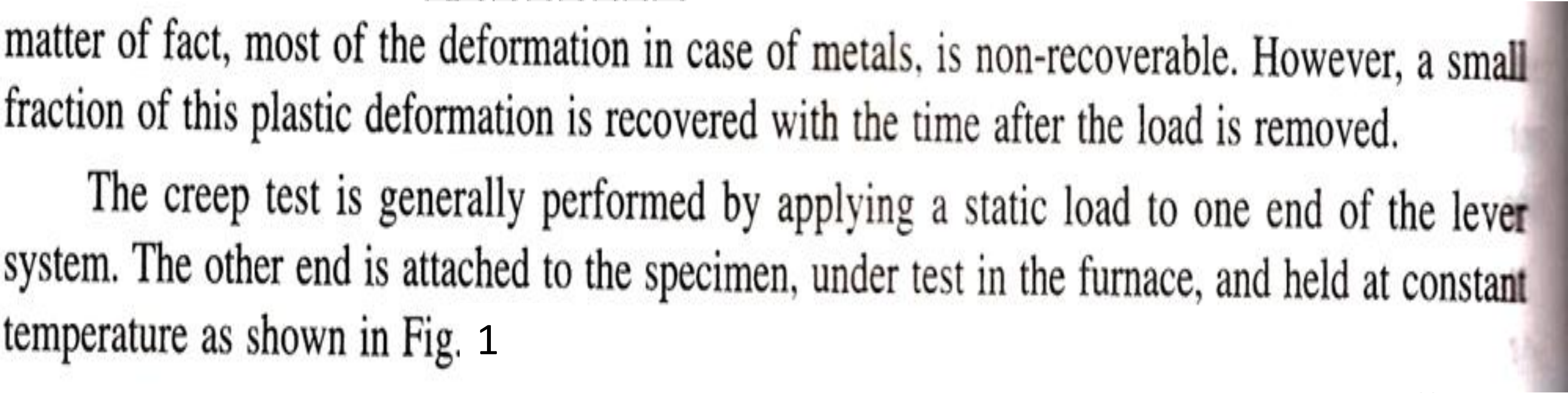
Notch toughness: represents the ability of a material to absorb energy usually determined under impact loading in the presence of a notch.

Creep Test



The continuous deformation of a metal, under a steady load, is known as creep. This test is very essential to predict the working life of some members or machine components which are subjected to creep. It is always exhibited in metals like iron, nickel, copper and their alloys at increased temperatures. But some metal like zinc, tin, lead and their alloys also creep at room temperatures. It has been observed that some organic metals such as plastics and rubber are very sensitive to creep.

Strictly speaking, the creep in metals is caused by slip occurring along crystallographic directions in the individual crystals together with some deformation of grain boundary. As a



matter of fact, most of the deformation in case of metals, is non-recoverable. However, a small fraction of this plastic deformation is recovered with the time after the load is removed.

The creep test is generally performed by applying a static load to one end of the lever system. The other end is attached to the specimen, under test in the furnace, and held at constant temperature as shown in Fig. 1

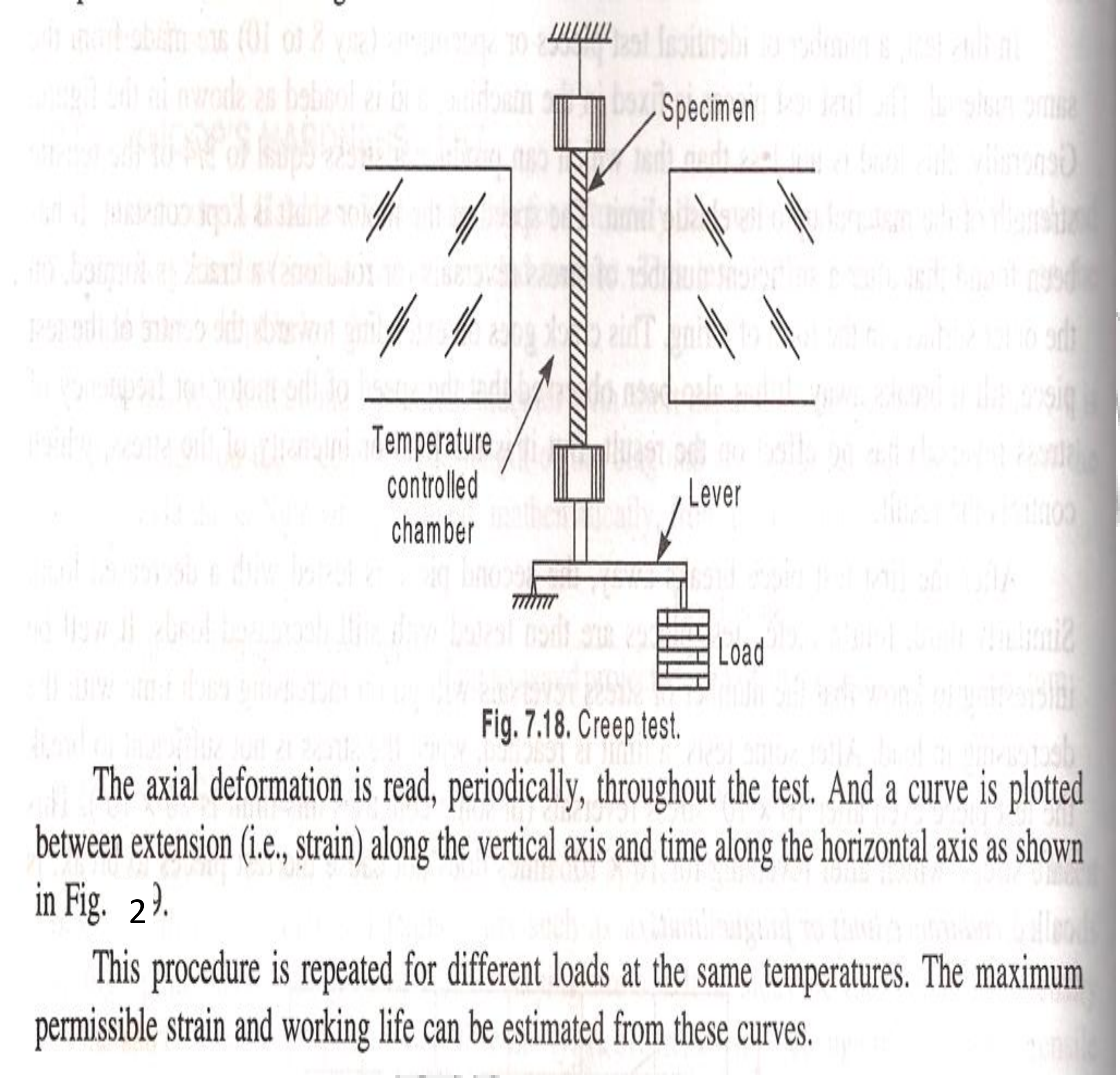


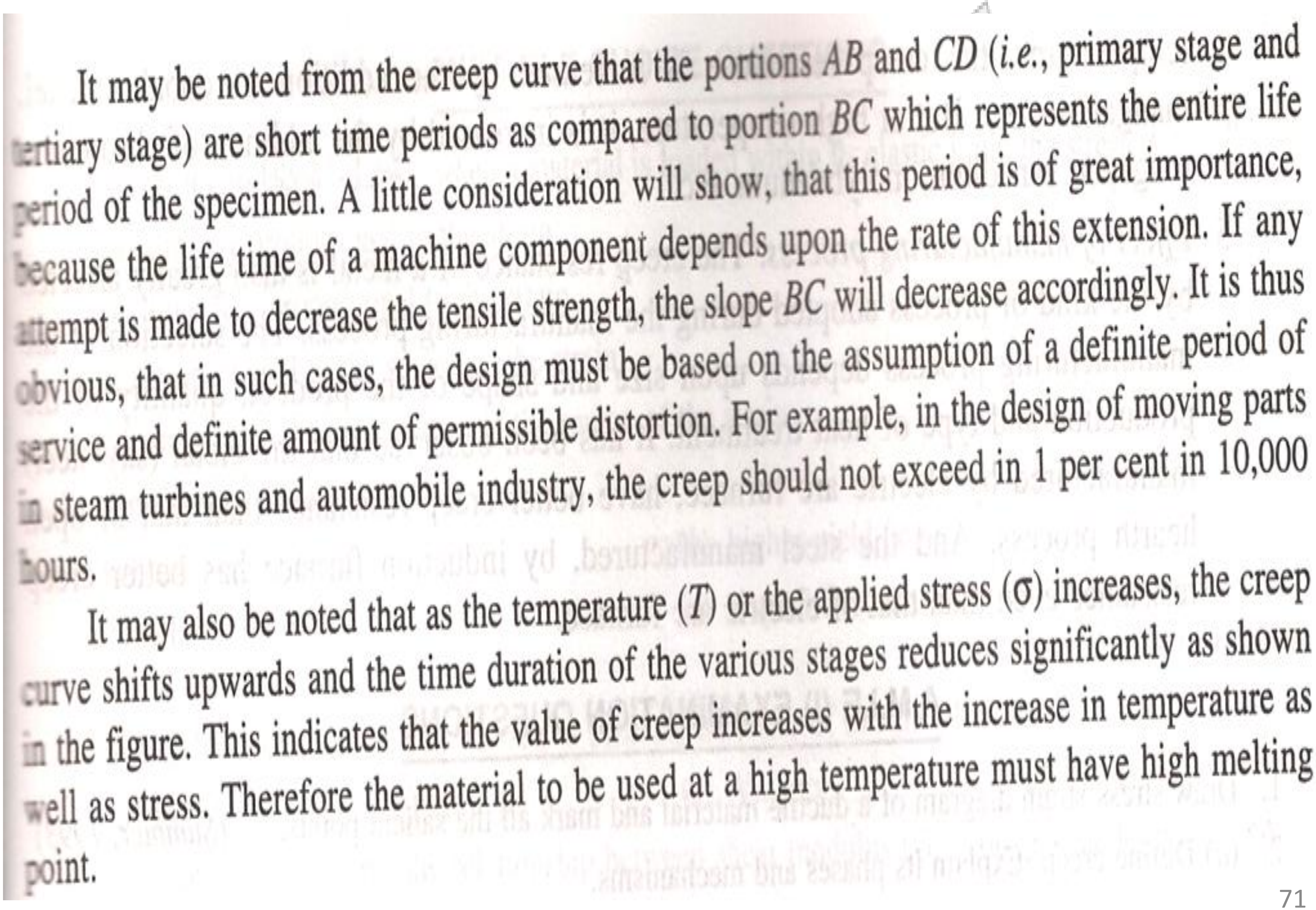
Fig. 7.18. Creep test.

The axial deformation is read, periodically, throughout the test. And a curve is plotted between extension (i.e., strain) along the vertical axis and time along the horizontal axis as shown in Fig. 2 9.

This procedure is repeated for different loads at the same temperatures. The maximum permissible strain and working life can be estimated from these curves.

Creep curves

Figure 2 shows the creep curves with stress and temperature effects



It may be noted from the creep curve that the portions *AB* and *CD* (*i.e.*, primary stage and tertiary stage) are short time periods as compared to portion *BC* which represents the entire life period of the specimen. A little consideration will show, that this period is of great importance, because the life time of a machine component depends upon the rate of this extension. If any attempt is made to decrease the tensile strength, the slope *BC* will decrease accordingly. It is thus obvious, that in such cases, the design must be based on the assumption of a definite period of service and definite amount of permissible distortion. For example, in the design of moving parts in steam turbines and automobile industry, the creep should not exceed in 1 per cent in 10,000 hours.

It may also be noted that as the temperature (*T*) or the applied stress (σ) increases, the creep curve shifts upwards and the time duration of the various stages reduces significantly as shown in the figure. This indicates that the value of creep increases with the increase in temperature as well as stress. Therefore the material to be used at a high temperature must have high melting point.

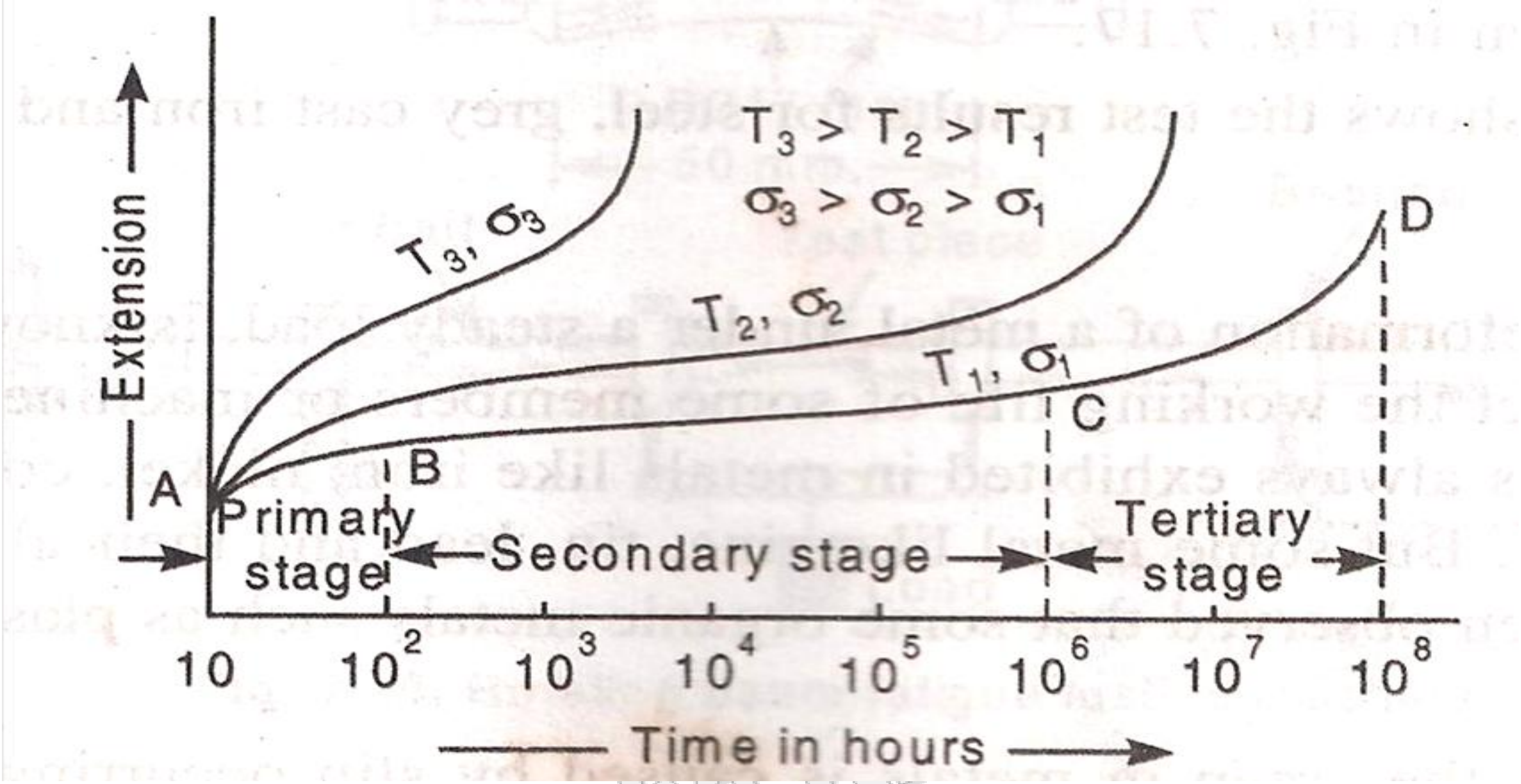


Figure 2: creep curves with stress and temperature effects

So with Increasing stress or temperature:

1. The instantaneous strain increases
2. The steady-state creep rate increases
3. The time to rupture decreases

The Critical Temperature for Creep is 40% of the Melting Temperature.

If $T > 0.40\ T_M$ → Creep Is Likely

- T_M = Melting temperature

Stages of creep curve

Most creep tests are conducted at constant load in analogous to engineering application, whereas creep tests at constant stress are necessary for understanding of mechanism of creep.

Figure 3 shows a typical creep curve with three stages of creep. The slope of the creep curve is designated as creep rate. Three stages may be observed in such a plot: (i) decreasing rate with time, (ii) approximately constant rate, (iii) increasing rate with time.

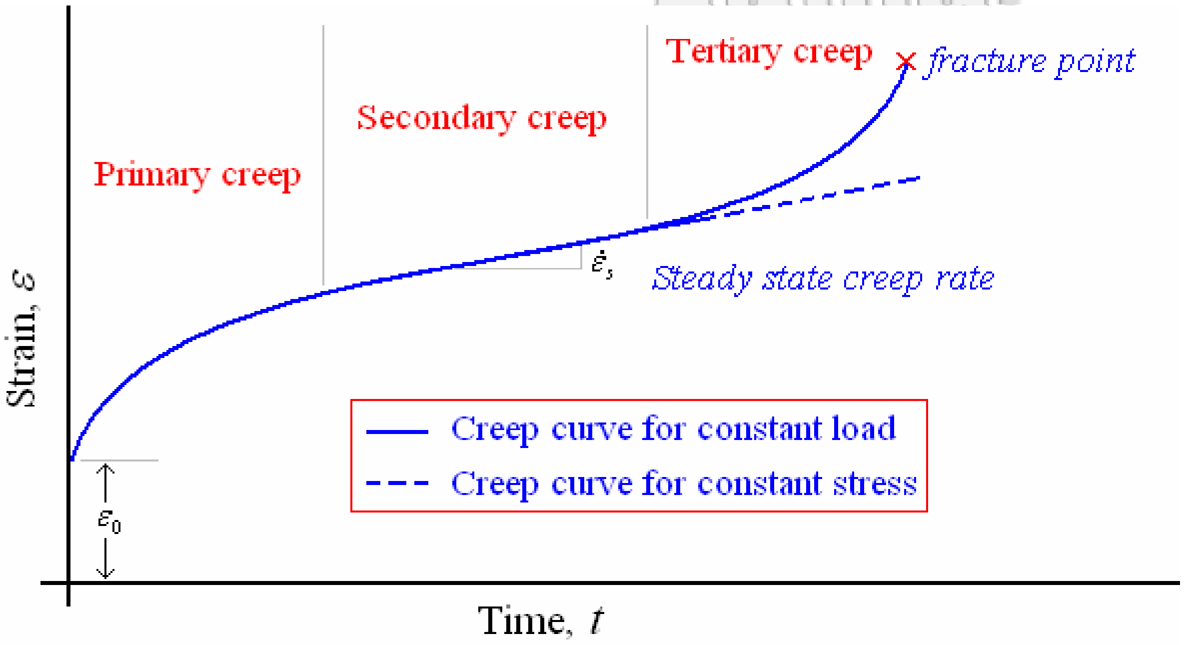


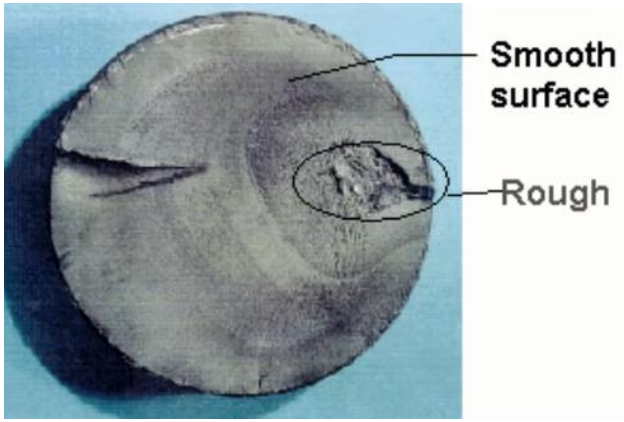
Figure 3: Typical creep curve

$$\dot{\varepsilon}_s = \Delta\varepsilon / \Delta t$$

ε_0 → Initial instantaneous strain

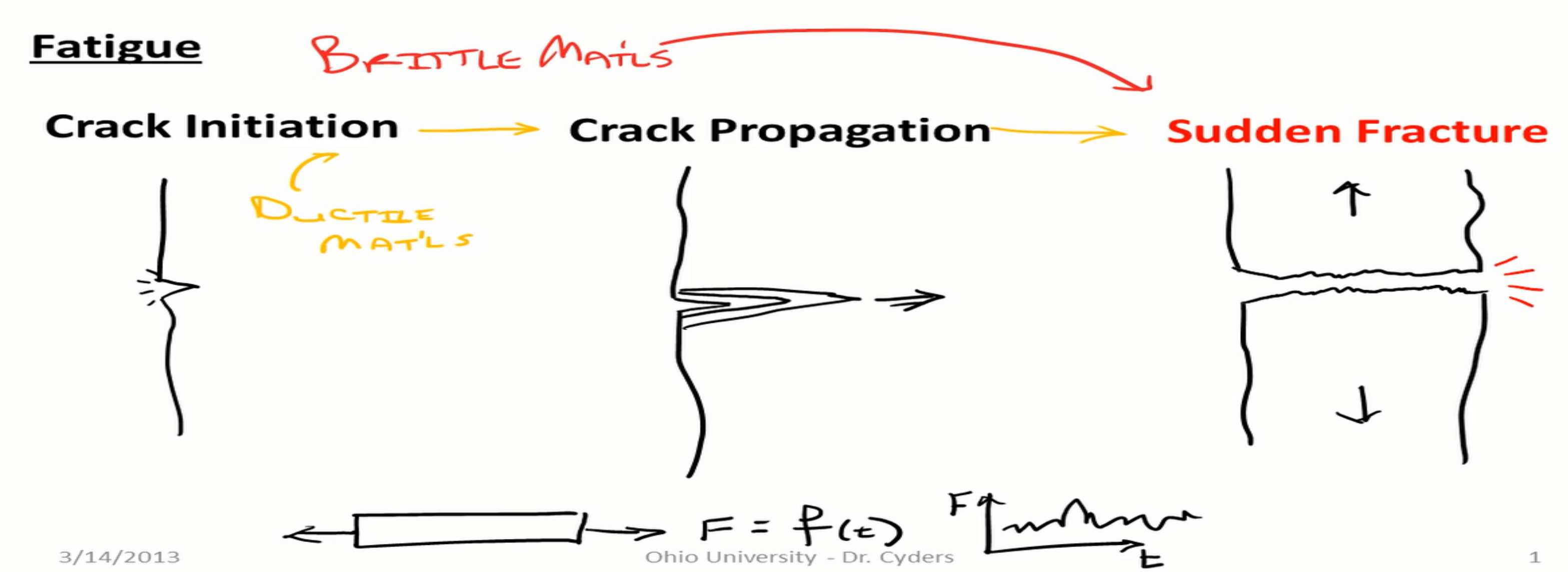
Fatigue fracture surface

Fatigue surface appears as a smooth region, showing beach mark or origin of fatigue crack.



Fatigue failure in an Aluminium bicycle crank. Dark area of striations: slow crack growth. Bright granular area: sudden fracture

Failure stages (the life of a fatigue crack)



Fatigue

Brittle Mat'ls

Crack Initiation → Crack Propagation → Sudden Fracture

Ductile Mat'ls

$F = f(t)$

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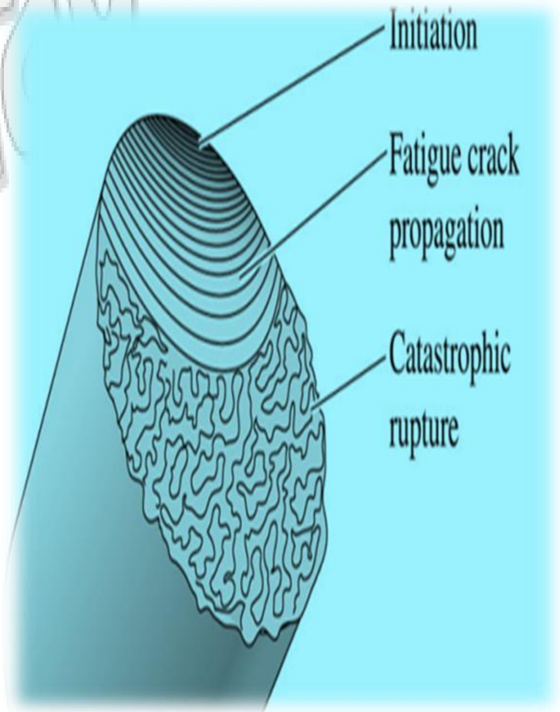
Failure stages are :

1. Crack initiation
2. Crack propagation
3. Final fracture.

The crack propagates from an initiating point such as a sharp corner, indent, flaw or other stress raiser.



1➢ Crack initiation (in notched specimens this stage may be absent). This occurs mostly at surfaces or sometimes at internal interfaces. Crack initiation may take place within about 10% of the total life of the component. Crack initiation in the areas of stress concentration

2➢Crack propagation

•Stage I short crack growth : growth of crack along planes of high shear stress. (something like deepening of the crack formed).

• Stage II stable crack growth: in this stage the crack grows along directions of maximum tensile stress.

3➢ Final fracture (end of life): reduction in load bearing area (due to crack propagation) leads to ultimate failure.

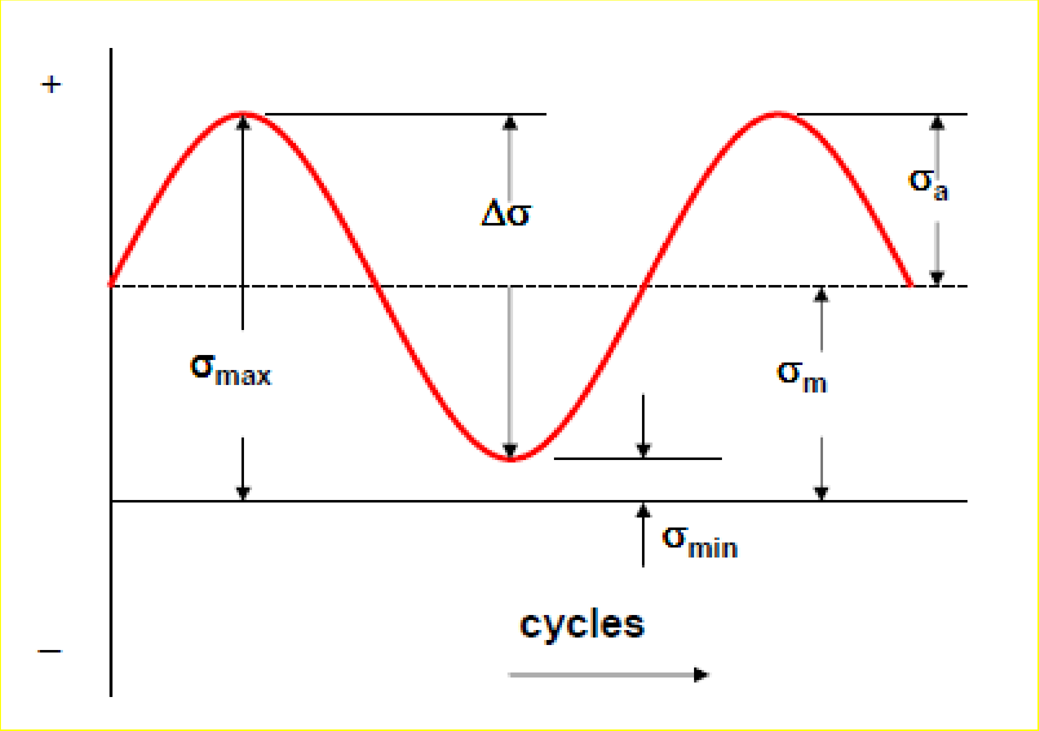
Definitions

Fatigue life(N): it is total number of cycles are required to bring about final fracture in a specimen at a given stress.

Fatigue limit or Endurance limit (S_e or σ_e): it is stress below which a material will not fail for any number of cycles. **Or** is the maximum stress that a material can endure for an infinite number of cycles without breaking.

Stress cycles

Nomenclature of stress parameter in fatigue loading



Fatigue stress cycle

Maximum stress, σ_{max}

Minimum stress, σ_{min}

Stress range

$$\Delta\sigma \text{ or } \sigma_r = \sigma_{\max} - \sigma_{\min} \qquad \text{Eq.1}$$

Alternating stress

$$\sigma_a = \frac{\Delta\sigma}{2} = \frac{\sigma_{\max} - \sigma_{\min}}{2} \qquad \text{Eq.2}$$

Mean stress

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \qquad \text{Eq.3}$$

Stress ratio

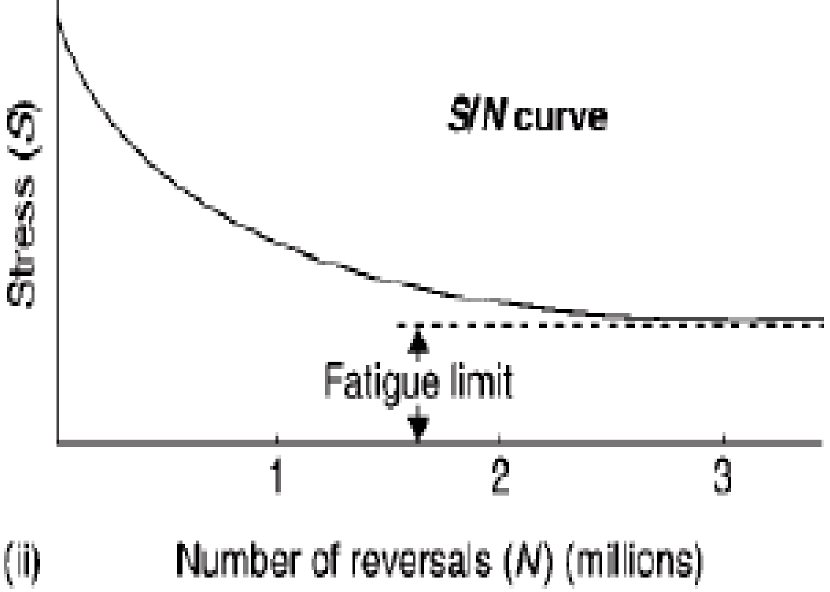
$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \qquad \text{Eq.4}$$

Amplitude ratio

$$A = \frac{\sigma_a}{\sigma_m} = \frac{1-R}{1+R} \qquad \text{Eq.5}$$

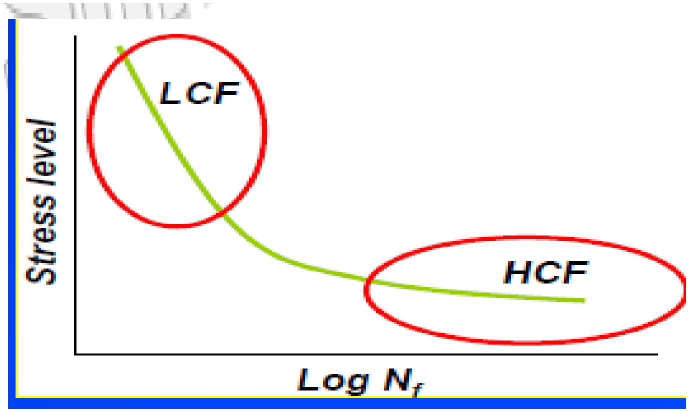
The S-N curve or Wohler curve

- S-N Curve is alternating stress amplitude (σ_a or S_a) versus number of cycles (N) to failure.
- Stress can be σ_a, σ_{max}, $\sigma_{min,}$ σ_m , R or A should be mentioned



- **HCF** high cycle fatigue (low strain) : fatigue failure at high numbers of cycles ($N > 10^5$) and low loads
- **LCF** low cycle fatigue (high strain) : fatigue failure at low numbers of cycles $N < 10^4$ or 10^5 and high loads.
- N increases with decreasing stress level

This mean $\boldsymbol{\sigma_m}$ or σ_a decreases with N.



Basquin equatiion

The S-N curve in the high-cycle region is sometimes described by the Basquin equation

σ_a = alternate stress amplitude

N= number of load reversals to failure

σ_f= fatigue strength coefficient defined by the stress intercept at 2N=1.

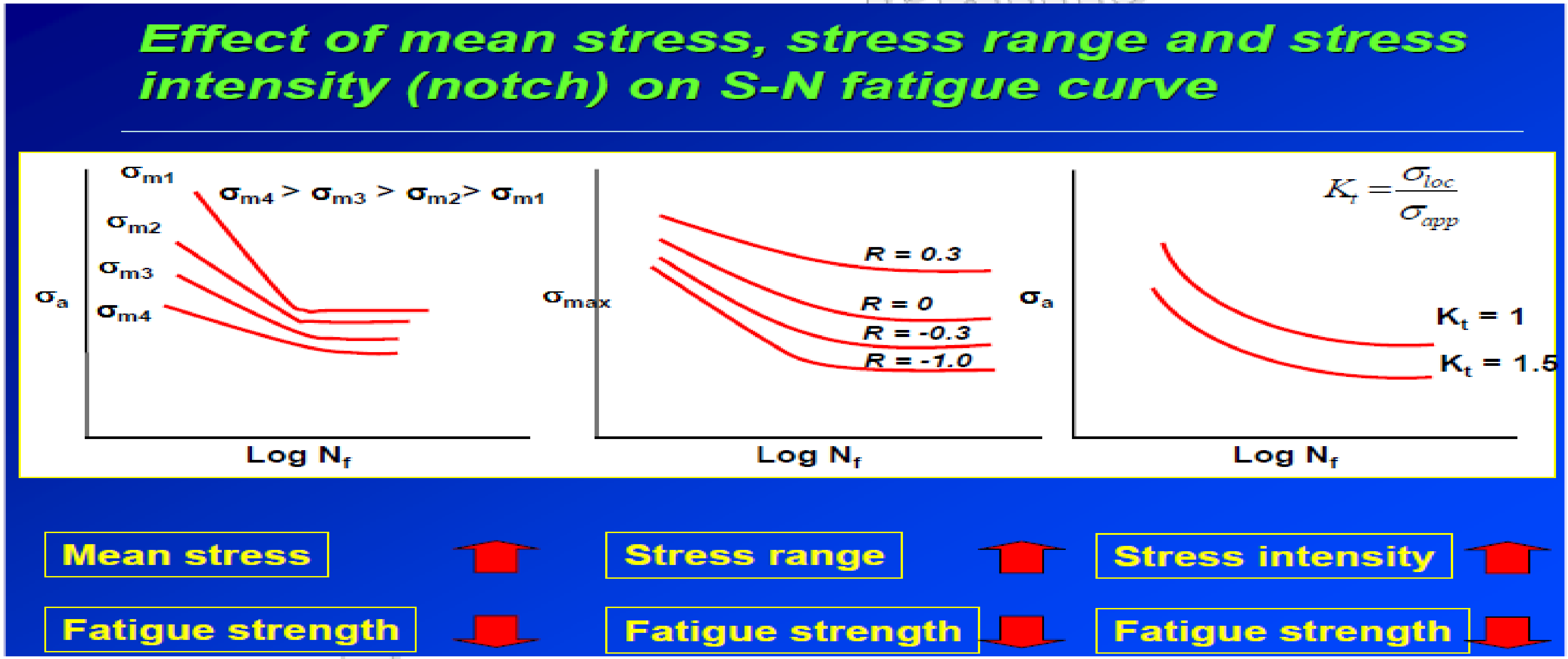
b= fatigue strength exponent, which varies between – 0.05 and -0.12 for most metals

$$\sigma_a = \sigma_f \ (2N)^b$$

Factors Affecting Fatigue Strength

1. Mean Stress
2. Surface Finish
3. Residual Stresses
4. Environmental effects
5. Stress concentration
6. Temperature

1. Mean Stress effect



Effect of mean stress, stress range and stress intensity (notch) on S-N fatigue curve

$$K_t = \frac{\sigma_{loc}}{\sigma_{app}}$$

Mean stress ↑ Stress range ↑ Stress intensity ↑

Fatigue strength ↓ Fatigue strength ↓ Fatigue strength ↓

Note: crack propagation has been measured as a function of the stress intensity factor