# **Mechanical Properties**

### Introduction

### **Tensile Force**

Pulls out of the cross-sectional area.

In the direction of force, length increases. Cross-sectional area decreases.

# **Compressive Force**

Pushes into the cross-sectional area.

In the direction of force, length decreases. Cross-sectional area increases.

#### **Stress**

Force per unit area.

$$\text{Stress } \sigma = \frac{\text{Force}}{\text{Area}} = \frac{F}{A}$$

### **Engineering stress**

Engineering stress 
$$\sigma = \frac{\text{Force}}{\text{Initial Area}} = \frac{F}{A_0}$$

#### **True stress**

$$ext{True stress } \sigma_T = rac{ ext{Force}}{ ext{Instantaneous Area}} = rac{F}{A_i}$$

#### Strain

Dimensional change with respect to the original dimensions.

### **Engineering strain**

Engineering strain 
$$\epsilon = \frac{\text{Extension}}{\text{Initial Length}} = \frac{l-l_0}{l_0}$$

True strain

True strain 
$$\epsilon_T = ln rac{l_i}{l_0}$$

## **Fracture**

Separation of a solid into more than 1 parts under load or stress.

Based on the type of load:

- Tensile fracture
- Compressive fracture
- Shear fracture
- Fatigue fracture
- Creep fracture

Characterized into 2:

- Ductile fracture
- Brittle fracture

### **Ductile fracture**

Materials show significant amount of plastic deformation prior to fracture. Fracture surface gives cup & cone appearance. Aka. cup-and-cone fracture.

Steps:

- 1. Specimen forms a neck
- 2. Cavities start to form within the neck
- 3. Cavities join with each other and form a crack
- 4. Crack propagates towards surface perpendicular to stress
- 5. Direction of crack changes to  $45^\circ$

#### **Brittle fracture**

Little or no plastic deformation prior to fracture. Fracture surface is smooth.

More dangerous than ductile fracture.

- No warning sign
- Crack propagates at very high speeds
- No need for extra stress during crack propagation.

## **Definitions**

⚠ TODO

This page is not very well organized.

# Elastic deformation (elasticity)

Deformation is temporary. Returns to its original shape when load is released.

#### Linear elastic materials

When elastic deformation portion in stress-strain diagram is straight line.

Young's modulus (aka Elastic modulus)

Young's modulus 
$$E = rac{ ext{stress}}{ ext{strain}} = rac{\sigma}{\epsilon}$$

Can be thought of as stiffness.

#### Nonlinear elastic materials

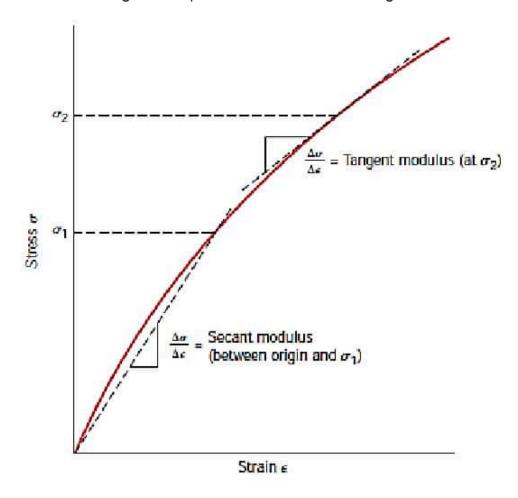
When elastic deformation portion in stress-strain diagram is not straight line.

#### Secant modulus

Equal to the tangent of the line connecting a point in the stress-strain diagram and the origin.

#### Tangent modulus

Equal to the instantaneous tangent on a point in the stress-strain diagram.



#### Poisson's ratio

A tensile stress in a particular direction causes extension (say  $\epsilon_z$ ) in that direction and contraction in other two directions ( $\epsilon_x$  and  $\epsilon_y$ ). For isotropic materials:

$$v=-rac{\epsilon_x}{\epsilon_z}=-rac{\epsilon_y}{\epsilon_z}$$

For metals (if not given) can be taken as v=0.34. Rubber's poisson's ratio is 0.5 which is the maximum possible value, mathematically.

#### Isotropic materials

Homogenous materials.  $\epsilon_x = \epsilon_y$ .

### Plastic deformation (plasticity)

When stress is not proportional to strain. Deformation is permanent or non-recoverable or plastic.

# Yield stress point

The point where plastic deformation starts in stress-strain diagram.

## Yield strength

Stress at yield stress point. Denoted by  $\sigma_y$ . Used when the strength of a metal is cited for design purposes.

True yield stress point is very difficult to find practically. Therefore **strain offset method** is used to find an approximate yield strength.

#### Strain offset method

A straight line is constructed parallel to the elastic portion of the stress-strain curve at some specified strain offset. The stress corresponding to the intersection of this line and the stress-strain curve is defined as the yield strength  $\sigma_y$ .

#### 0.2% proof stress

Yield strength when 0.002 is used in strain offset method.

### (i) For steel

Yield strength is taken as the average stress at the lower yield point. Strain offset method is not required. Upper yield point occurs because of C atoms, and is specific to steel.

# Tensile strength

After yielding, the stress necessary to continue plastic deformation increases to a maximum, and then decreases.

### **Ultimate tensile strength (UTS)**

The maximum stress that can be sustained by a material in tension.

$$ext{UTS} = rac{ ext{max load}}{ ext{original cross-sectional area}}$$

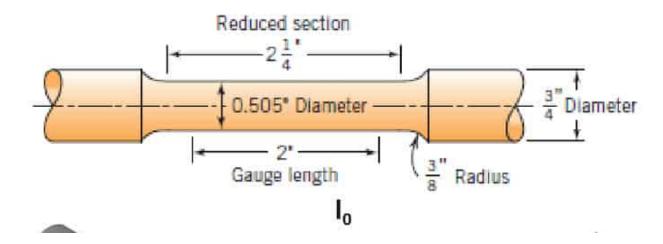
# **Tensile Test**

Stress-strain plot will be produced in the test.

# **Testing setup**

Follows ASTM Standards E 8 and E 8M. (American Society for Testing and Materials).

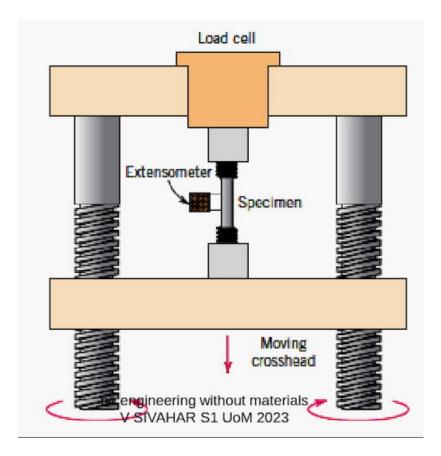
The specimen:



Here

- ullet Gauge length  $l_0$
- Initial diameter  $d_0$
- ullet Initial area  $A_0=rac{\pi {d_0}^2}{4}$

#### The setup:



Test will be done until the specimen fractures. Results are converted to engineering stress and strain, and plotted.

#### Load cell

Measures the force applied to the specimen.

#### **Extensometer**

Used to measures the elongation (increase in length) in the specimen.

#### For brittle material

The  $\sigma$ - $\epsilon$  behavior of brittle materials cannot be assessed by a tensile test because:

- Difficult to prepare test specimens
- Difficult to grip brittle materials without fracturing them

Hence, fracture strength is specified for engineering design purposes. Tensile strength is calculated from its **modulus of rupture (MOR)** or **flexural strength** value.

### Tensile strength $\times 1.3 = MOR$

# **Necking**

All deformation up to the maximum point is uniform throughout the specimen.

At this maximum stress, a neck begins to form – known as necking. All subsequent deformation is confined to this neck.

## **Stress Strain Plot**

#### **Observables**

- Elastic region
- Yield point
- Proof stress
- Plastic portion
- Steadily decreasing slope
- Ultimate tensile strength
- Localization of the deformation
- Young's modulus
- Upper and lower yield stresses
- Fractural strength

#### (i) Note

After yield point, gradient of the stress-strain curve decreases up to the necking point. This is an indication that the material is becoming stronger and harder.

#### Stiff

Area under the curve, until the yield point. Higher area means the higher stiffness.

### Strong/strength

• For ductile materials: <u>yield stress</u>

• For brittle materials: fracture stress

#### **Flexible**

Higher strain in elastic region.

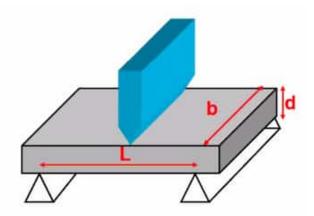
#### Weak

Opposite to strengthness.

## Greatest percentage elongation

Maximum strain or failure strain.

# **Flexural Test**



Support the material at 2 ends. Apply pressure perpendicular to the material until the material fractures. 3-point bending is used here.

$$ext{MOR} = rac{3PL}{2bd^2}$$

Here:

- ullet length
- b width
- ullet d depth

# **Ductility**

A measure of the degree of plastic deformation at fracture.

Most metals are ductile. Ductile materials have high tensile strength.

Percentage elongation

$$rac{l_f-l_0}{l_0} imes 100$$

Percentage reduction in area

$$rac{A_0-A_f}{A_0} imes 100$$

#### **Brittle**

A material that experiences very little or no plastic deformation.

Brittleness order: Ionic bonds > Covalent bonds > Metallic bonds

# Malleability

Ability of a material to undergo plastic deformation under compression.

(i) Note

All ductile materials are malleable. Converse is not true.

# **Ductility & Brittleness**

Depends on:

- Composition of the material
- Temperature

# **Ductile-Brittle Transition**

Ductile materials show brittle behavior as the temperature is lowered. This is known as ductile-brittle transition.

Ductile-brittle transition behavior of materials is studied by performing impact test over a range of temperatures.

The transition behavior is:

- Sudden in BCC metals (eg: Steel)
- Gradual in FCC metals (eg: Copper)

# **Ductile-Brittle Transition Temperature**

The temperature which a material is:

- brittle below the temperature
- ductile above the temperature

Many steels exhibit this behaviour.

i Note

Titanic sunk because of this transition.

# **Work Hardening**

Strength and hardness of a metal increases as a result of plastic deformation. This process is called work hardening.

Increases:

- strength
- hardness

#### Decreases:

- ductility
- toughness

# **Steps**

- Specimen is loaded onto a tensile test apparatus
- Test is stopped after the specimen has gone under plastic deformation
- Specimen is unloaded and reloaded
- ullet New  $\sigma-\epsilon$  diagram will have a increased yield strength

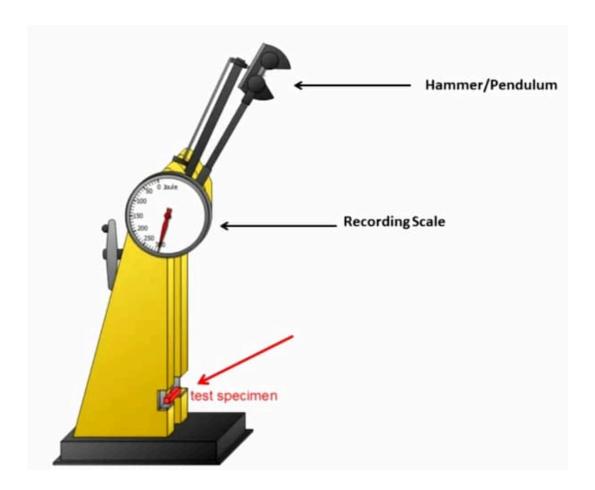
# **Toughness**

Maximum strain energy, a material can absorb upto fracture. Area under the  $\sigma-\epsilon$  graph is a measure of toughness. Can be measured by impact test.

Generally ductile materials have a high toughness compared to brittle materials.

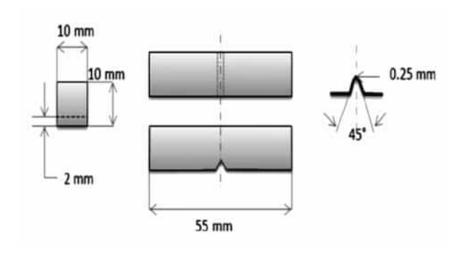
# **Charpy Impact Test**

# **Tester**



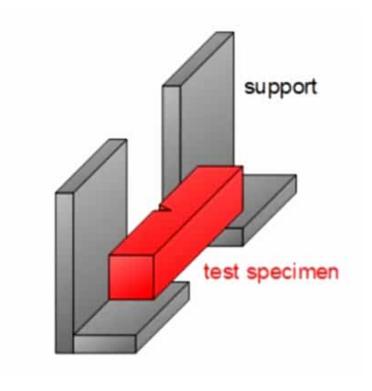
# Specimen

According to ASTM-E 23.



Specimen is notched to keep the crack straight.

#### Loaded state



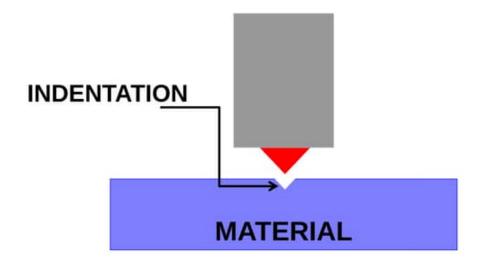
# **Hardness**

Hardness of metals is defined as resistance to indentation. Can be measured by indentation test...

When 2 surfaces are rubbing against each other, hardness is important. Materials with less hardness will be worn off quickly. Only materials with high hardness, can cut through materials with light hardness. Diamond is the hardest material.

# **Indentation Test**

Metal is subjected to indentation with a hard indenter. Depth of the indent is a measure of hardness.



Hardness units differ with the type of indenter used and the load applied.

### **Units**

#### **Brinell (HB)**

- 10 mm diameter steel / WC ball indenter
- Any load can be applied
- Diameter of the indentation is measured instead of the depth

$$HB=rac{2F}{\pi D(D-\sqrt{D^2-d^2})}$$

#### Here:

- F applied load (in kN)
- D diameter of the indenter
- d diameter of the indentation
- h depth of the indentation

### (i) Note

Load is measured in kN and lengths are measured in mm.

#### Vickers (HV)

- Pyramid shaped indenter made of diamond
- Any load can be applied
- ullet Diagonal lengths d1 and d2 of the diamond-shape indentation are measured
- ullet Average d is used in the calculation

#### (i) Note

Angle between the diamond faces is  $136\,\mathrm{degrees}$ .

$$HV=rac{1.854\,F}{d^2}$$

#### Rockwell (HR)

Not accurate enough to be used in academic level (or where accuracy is important). Industrially preferred because of ease of measurement. Only 3 load options.

Туре	Load	Indenter
HRA	60kg	Cone-shaped indenter. Made of diamond.
HRD	100kg	Cone-shaped indenter. Made of diamond.
HRC	150kg	Cone-shaped indenter. Made of diamond.
HRF	60kg	1/16" diameter (1.5mm approx.) ball made of steel
HRB	100kg	1/16" diameter (1.5mm approx.) ball made of steel
HRG	150kg	1/16" diameter (1.5mm approx.) ball made of steel
HRE	100kg	1/8" diameter (3mm approx.) ball

(i) Note

No need to remember the above data.

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