



**Department of Mechanical Engineering  
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**Materials Science for Engineers – ME242TB  
Unit II**

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## Material behaviour-----10 Hours

**Thermal properties** : thermal conductivity, thermoelectric effects, heat capacity, thermal expansion coefficient, thermal shock, thermocouple.

**Electrical Properties** : dielectric behaviours and temperature dependence of the dielectric constant, insulating materials, ferroelectricity, piezoelectricity, super conductor.

**Optical properties** : luminescence, optical fibers

**Mechanical Properties** : Stress-strain diagram, elastic deformation, plastic deformation, hardness, viscoelastic deformation, impact energy, fracture toughness, fatigue.

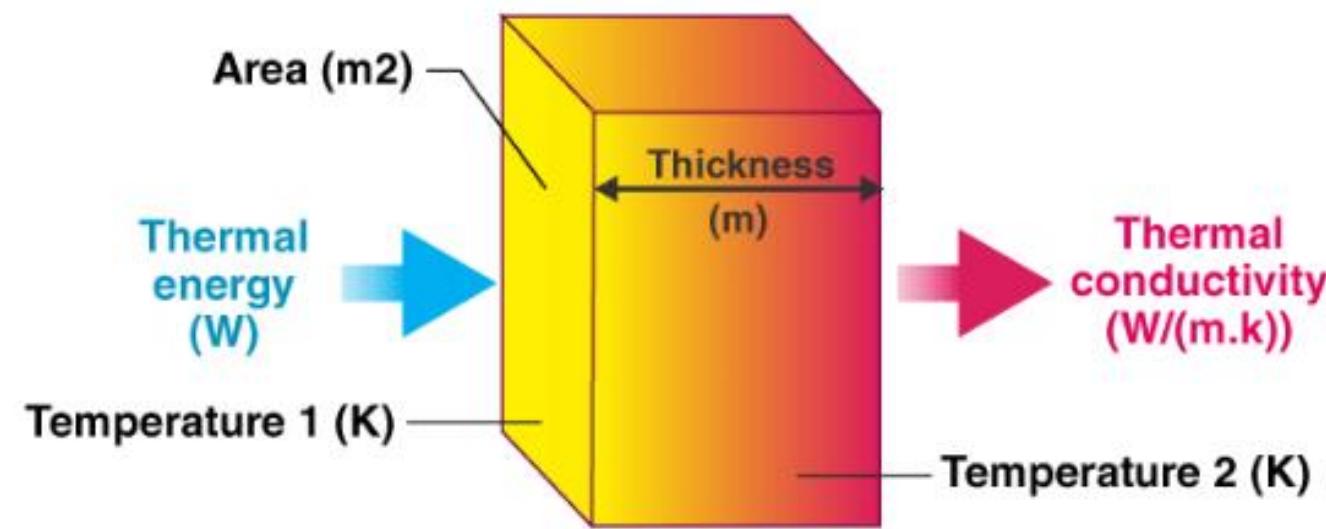


# Thermal Properties

**Thermal conductivity** refers to the ability of a given material to conduct/transfer heat. It is generally denoted by the symbol ‘ $k$ ’ but can also be denoted by ‘ $\lambda$ ’ and ‘ $\kappa$ ’. The reciprocal of this quantity is known as thermal resistivity. Materials with high thermal conductivity are used in heat sinks whereas materials with low values of  $\lambda$  are used as thermal insulators. Every substance has its own capacity to conduct heat. The thermal conductivity of a material is described by the following formula:

$$K = - (QL) / (A\Delta T) \text{ Where,}$$

$K$  is the thermal conductivity in  $\text{W/m.K}$ ,  $Q$  is the amount of heat transferred through the material in Joules/second or Watts,  $L$  is the distance between the two isothermal planes,  $A$  is the area of the surface in square meters,  $\Delta T$  is the difference in temperature in Kelvin



**Thermal conductivity** is influenced by factors such as:

- Material composition (e.g., atomic structure).
- Temperature (thermal conductivity can vary with temperature).
- Impurities or defects within the material.

Example:

- Copper: High thermal conductivity (~400 W/m·K).
- Glass: Low thermal conductivity (~0.8 W/m·K)

**Thermal conductivity** plays a crucial role in engineering, as it helps design systems and structures that manage heat efficiently. Here are some of the key applications:

- **Thermal Insulation:** Materials with low thermal conductivity (e.g., foam, fiberglass) are used in buildings, appliances, and industrial equipment to reduce heat transfer and maintain energy efficiency.
- **Heat Exchangers:** High-conductivity materials like copper or aluminum are used in heat exchangers (e.g., radiators, condensers) to transfer heat effectively between fluids.

- **Electronics Cooling:** In devices like computers and smartphones, materials with high thermal conductivity, such as thermal paste or heat sinks, are used to dissipate heat generated by processors and circuits.
- **Refrigeration and HVAC Systems:** Thermal conductivity is considered when designing cooling and heating systems, ensuring efficient energy transfer and temperature control.
- **Thermal Protection in Aerospace:** Spacecraft and aircraft require materials with specific thermal properties to handle extreme conditions like heat during re-entry or cold in space.
- **Manufacturing Processes:** In processes like welding, casting, and molding, understanding thermal conductivity helps control heat flow and achieve desired results in shaping or joining materials.

**Heat capacity** is defined as the amount of heat energy required to raise the temperature of a given quantity of matter by one degree Celsius.

Heat capacity for a given matter depends on its size or quantity and hence it is an extensive property. The unit of heat capacity is joule per Kelvin or joule per degree Celsius

**Specific heat capacity**, or **specific heat** (often denoted as 'c') is the amount of heat energy required to change the temperature of one gram (or one kilogram) of a substance by one degree Celsius (or Kelvin).

Units for specific heat are joules per gram per degree Celsius ( $J/g \cdot {}^\circ C$ ) or joules per kilogram per degree Celsius ( $J/kg \cdot {}^\circ C$ ).

Specific Heat can be calculated using the formula:  $Q = mc\Delta T$ , where:

$Q$  = heat energy (in Joules),  $m$  = mass of the substance (in grams or kilograms),  $c$  = **specific heat capacity** of the substance (in  $J/g \cdot {}^\circ C$  or  $J/kg \cdot {}^\circ C$ ),  $\Delta T$  = change in temperature (in  ${}^\circ C$  or K)

## Factors Affecting Specific Heat:

- **Type of Substance:** Different substances have different specific heat capacities. For example, water has a high specific heat capacity, while metals tend to have lower specific heat capacities.
- **Mass:** The amount of heat needed to change the temperature of a substance is directly proportional to its mass.

## Examples:

- Water has a high specific heat capacity, meaning it takes a lot of energy to raise its temperature. This is why water heats up and cools down relatively slowly compared to other substances.
- Sand has a low specific heat capacity, meaning it heats up and cools down quickly.

## Importance:

**Designing** efficient heating and cooling systems, **Chemistry**: Studying heat transfer and reactions, **Meteorology**: Understanding climate patterns, **Calorimetry**: Specific heat capacity is often determined experimentally using a calorimeter, a device that measures heat flow.

The **coefficient of thermal expansion** describes how much a material expands or contracts in response to temperature changes, with different types (linear, area, volumetric) depending on the dimension considered.

Thermal expansion is the tendency of matter to change in volume in response to changes in temperature.

When a substance is heated, its constituent particles move faster, increasing the average distance between them, leading to expansion. Conversely, when a substance is cooled, the particles move slower, decreasing the average distance and leading to contraction.

Types of Thermal Expansion Coefficients:

## Coefficient of Linear Thermal Expansion (Linear CTE) ( $\alpha$ ):

This measures the change in length per unit length per degree change in temperature.

$$\Delta L = \alpha L \Delta T, \alpha = \Delta L / L \Delta T \rightarrow \alpha = \varepsilon / \Delta T \quad (\text{as } \varepsilon \text{ is mechanical strain})$$

where  $\Delta L$  is the change in length,  $L$  is the original length,  $\Delta T$  is the change in temperature, and  $\alpha$  is the coefficient of linear thermal expansion.

## Factors Affecting Thermal Expansion coefficient

- **Material:** Different materials have different coefficients of thermal expansion.
- **Temperature Change:** The larger the temperature change, the greater the expansion or contraction.
- **Initial Size:** The larger the initial size of the object, the greater the change in size with temperature.

## Applications of Thermal Expansion:

- **Bimetallic Strips:** Used in thermostats and other temperature-sensitive devices.
- **Railroad Tracks:** Expansion joints are used to prevent buckling due to thermal expansion.
- **Thermometers:** The expansion of mercury or alcohol is used to measure temperature.
- **Engine Coolants:** The expansion of fluids in engine cooling systems is taken into account in design.
- **Construction:** Thermal expansion is considered in the design of bridges, buildings, and other structures to prevent damage.

**Thermal shock resistance** is the property that allows a material to endure sudden temperature variations, whether heating or cooling, without cracking or failing.

This is crucial in applications where materials experience extreme temperature fluctuations, such as in furnace parts, rocket nozzles, and fusion reactors.

## Importance:

Rapid temperature changes can cause uneven expansion and contraction within a material, leading to stresses that can cause cracks or failure, especially in brittle materials like ceramics.

**Thermal shock resistance (TSR)** can be explained using the equation

$$TSR \cong \frac{\sigma_f k}{E\alpha}$$

Where  $\sigma_f$  - fracture toughness,  $k$  - thermal conductivity,  $E$  - Young's modulus,  $\alpha$  - thermal expansion coefficient

## Factors influencing thermal shock resistance:

- **Fracture toughness:** Materials with high fracture toughness can withstand more stress before cracking.
- **Thermal conductivity:** High thermal conductivity allows heat to be distributed quickly and evenly, minimizing temperature gradients and reducing stress.

## Factors influencing thermal shock resistance:

- **Young's modulus:** A lower Young's modulus (a measure of stiffness) can also contribute to better thermal shock resistance.
- **Thermal expansion coefficient:** Materials with low thermal expansion coefficients tend to have better thermal shock resistance because they expand and contract less with temperature changes, reducing stress.

## Materials with good thermal shock resistance:

- **Silicon nitride:** Known for its high heat tolerance and ability to withstand rapid cooling.
- **Borosilicate glass:** Used in laboratory equipment and high-temperature applications due to its resistance to thermal shock.
- **C-C composites:** Excellent resistance to thermal shock, making them suitable for refractory applications.
- **ZTA composites and zirconia:** Isotropic ceramics with low expansion coefficients and high thermal shock resistance.

**Thermoelectric effects** describe the relationship between temperature differences and electrical phenomena, encompassing the Seebeck, Peltier, and Thomson effects, where temperature gradients can generate voltage or vice versa.

The thermoelectric effect is essentially the direct conversion of heat energy into electrical energy (and vice versa).

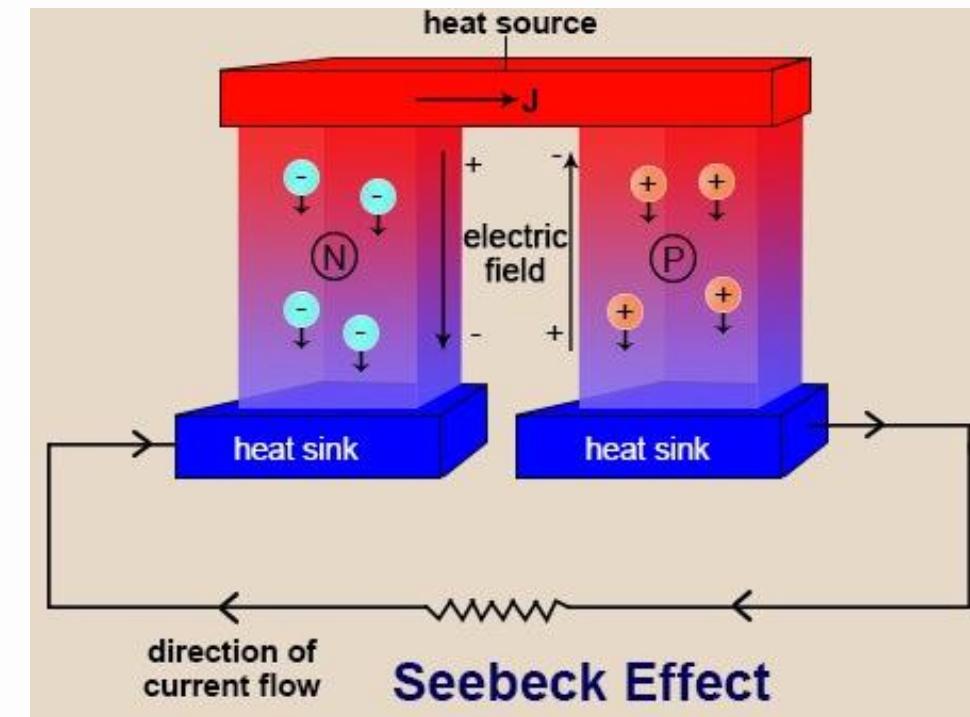
This conversion happens through the movement of electrons or holes (charge carriers) in materials when a temperature difference is applied. When a temperature gradient exists across a material, charge carriers diffuse from the hot side to the cold side, resulting in a voltage difference.

The **Seebeck effect** is a phenomenon that creates an electrical voltage when there is a temperature difference between two different materials.

It's a thermoelectric effect, which means it involves the conversion of heat into electricity.

## Working Principle

- Two different materials are connected to form a junction
- One junction is heated, while the other is kept cool
- Electrons flow from the hot junction to the cold junction
- This creates an imbalance of charge and spin between the junctions
- The imbalance results in an electric potential and a magnetic field
- The electric potential drives an electric current through the loop

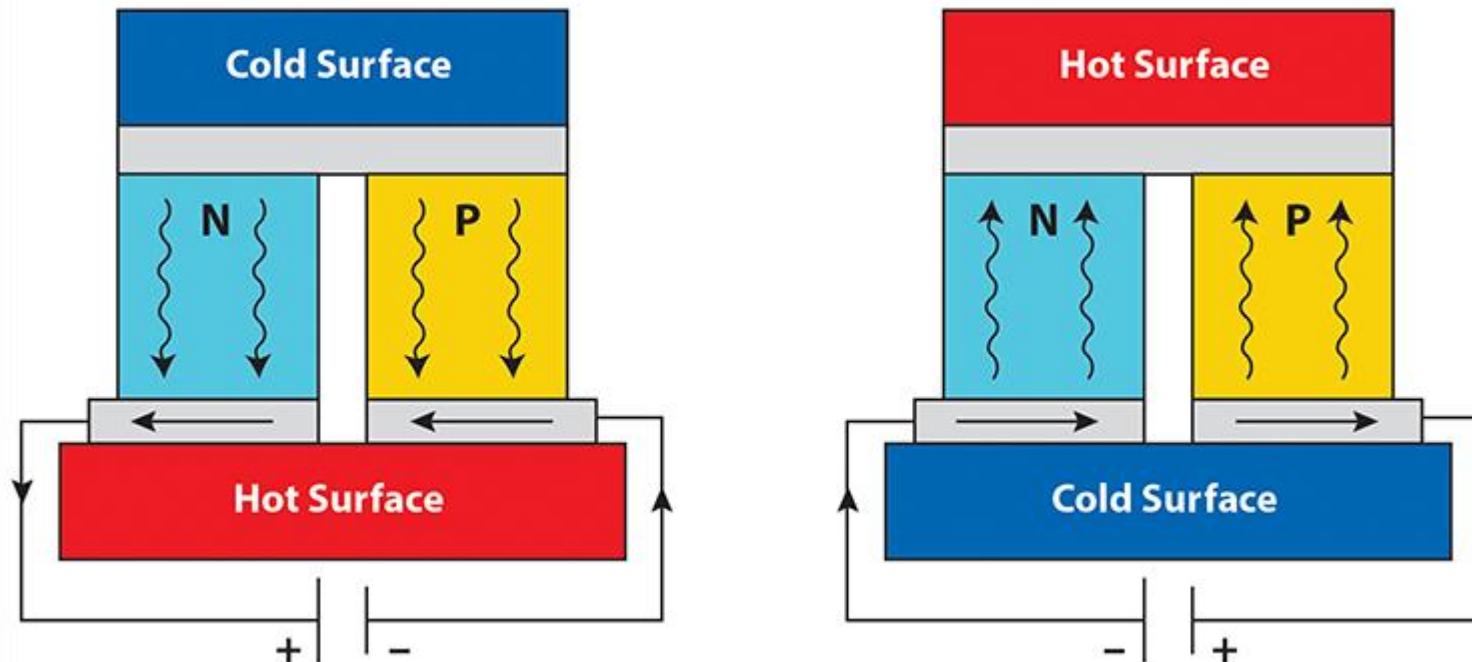


## Applications

Used in thermocouples to measure temperature, Convert waste heat into electrical power , NASA uses the Seebeck effect to power science missions in extreme environments

**The Peltier effect** is the reverse of the Seebeck effect. It occurs when an **electric current** is passed through a junction of two dissimilar materials, resulting in a **transfer of heat** (absorption or release) across the junction.

- Heat is absorbed at one junction and released at the other.
- The direction of heat flow depends on the direction of the current.



**Application :** This effect is utilized in thermoelectric cooling devices, like thermoelectric coolers (TECs) or Peltier coolers, commonly found in applications such as refrigeration, CPU cooling, and portable refrigerators.

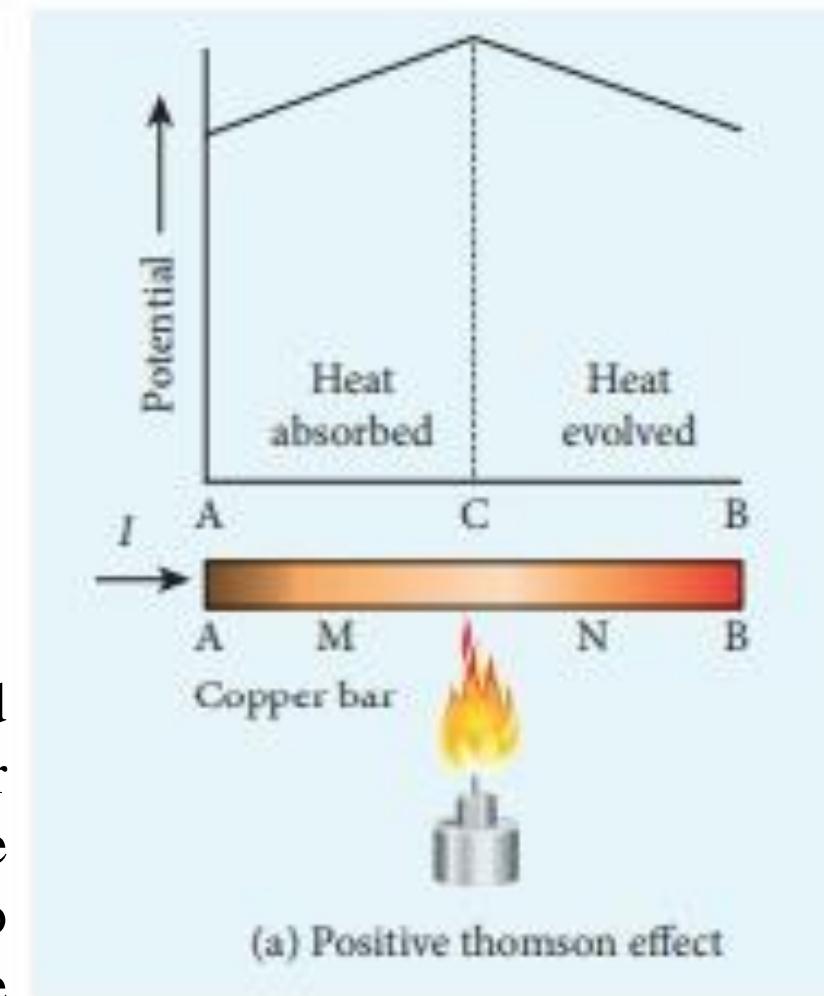
## Thomson Effect:

It is a thermoelectric phenomenon describing how heat is absorbed or released in a material when an electric current flows through it in the presence of a temperature gradient. The Thomson Effect occurs within a single material.

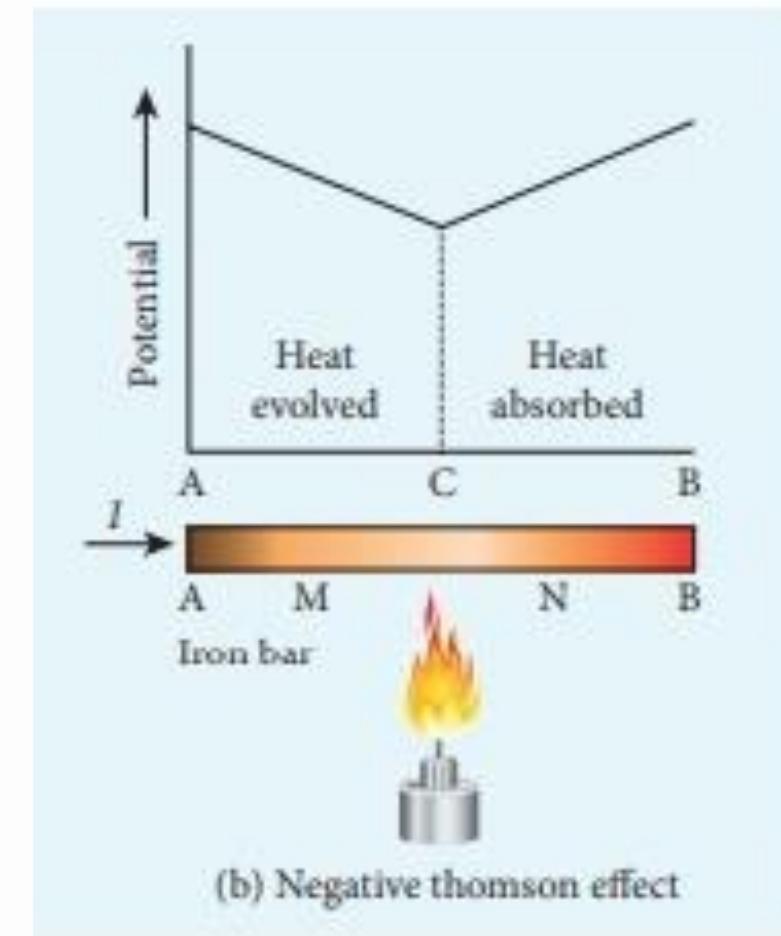
**Explanation:** The Thomson effect involves a change in temperature along the length of the conductor itself, leading to a heat exchange.

**Applications:** Thermoelectric generators, Thermocouples, Temperature sensors, Energy harvesting

When current is passed through a copper bar AB (Figure a) and heated at the middle point C, the point C will be at higher potential. Heat is absorbed along AC and evolved along CB of the conductor as shown in Figure (a). Thus heat is transferred due to the current flow in the direction of the current. It is called positive Thomson effect. Similar effect is observed in metals like silver, zinc, and cadmium.



When the copper bar is replaced by an iron bar, heat is evolved along CA and absorbed along BC. Thus heat is transferred due to the current flow in the direction opposite to the direction of current. It is called negative Thomson effect as shown in the Figure (b). Similar effect is observed in metals like platinum, nickel, cobalt, and mercury.

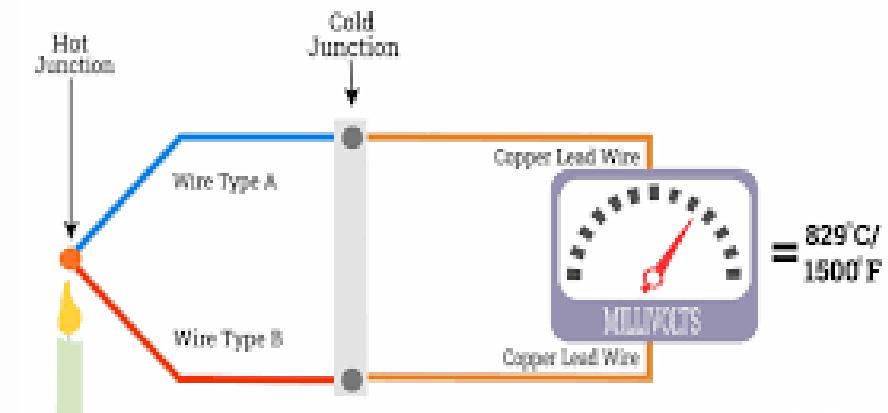


**Thermocouple:** A thermocouple is a temperature sensor that consists of two different metal wires joined at one end. It generates a voltage proportional to the temperature difference between the two ends.

## Working Principle:

1. Two dissimilar metals are joined at one end to form a junction.
2. One end of the junction is heated, while the other end is kept at a known temperature.
3. A small current flows through the junction.
4. The voltage is measured using a voltmeter.
5. The voltage is correlated to the temperature using calibration data

**Materials:** Common thermocouple materials include combinations like **Type K** (chromel/alumel), **Type J** (iron/constantan), and **Type T** (copper/constantan).



## Applications:

**Temperature Measurement:** Thermocouples are widely used for measuring temperatures in manufacturing, food processing, and HVAC systems.

**Thermoelectric Devices:** thermoelectric generators and coolers.



# Electrical Properties

**Dielectric behaviour** refers to the properties of an electrical insulator (dielectric material) when subjected to an electric field, resulting in the displacement of charges and the formation of electric dipoles, which can be described by concepts like dielectric constant, permittivity, and electric polarization.

Dielectric properties of materials are defined as a molecular property that is fundamental in all the materials that are capable of impending electron movement, resulting in polarisation within the material on exposure to an external electric field.

Dielectric materials are insulators, resist the flow of electric current and characterized by a high resistance to electrical conductivity and with a relatively high dielectric constant.

## Dielectric Polarization:

When a dielectric material is placed in an electric field, the positive and negative charges within the material do not flow freely like in a conductor, but instead, they experience a slight displacement or shift. This shift results in the formation of electric dipoles, where the positive and negative charge centres are no longer aligned causing dielectric polarisation.

## Dielectric Constant ( $\epsilon$ ):

A measure of how easily a material can be polarized, indicating its ability to **store electric energy** in an electric field. The dielectric constant, also known as relative permittivity, is a unitless and dimensionless quantity because it's the ratio of a material's permittivity to the permittivity of free space

Essentially, it is a measure of how well a material can be polarized under the influence of an external electric field.

## Examples of Dielectric Materials:

Common examples include plastics, rubber, glass, ceramics, and various gases

**Dielectric Strength:** It is defined as the maximum **electric field** a dielectric material can endure/ withstand without electrical breakdown or failure. It is often measured in units of volts per unit thickness (V/m or kV/mm).

It is a key parameter in designing and using insulating materials, particularly in applications such as electrical insulation and high-voltage systems.

## Factors Influencing Dielectric Strength:

- **Material Composition**
- **Purity of the Material:** Impurities or defects within the material can weaken its dielectric strength.
- **Temperature:** Dielectric strength can be influenced by temperature. In some cases, it may decrease with increasing temperature due to thermal effects on the material.
- **Thickness:** Generally, thicker materials have higher dielectric strength. This is an important consideration in the design of insulating layers.
- **Rate of Voltage Application:** The dielectric strength can depend on the rate at which the electric field is applied. Rapid changes in voltage may affect breakdown characteristics.

## Effect of Temperature on Dipole Orientation:

- **Polar Materials:** In materials with permanent electric dipoles, higher temperatures lead to increased thermal agitation, making it harder for dipoles to align with an electric field, thus reducing the dielectric constant.
- **Non-polar Materials:** In materials without permanent dipoles, temperature affects the polarizability of atoms and molecules, which can lead to a slight increase in dielectric constant with temperature

# Temperature dependence of the dielectric constant

**Temperature dependence of the dielectric constant:** The temperature dependence of the dielectric constant varies depending on the type of material. Here are some general trends.

- Dielectric Constant Increases with Temperature:** In some materials, especially **ferroelectric** materials [**Lead titanate**(PbTiO<sub>3</sub>), **Lead zirconate titanate**(PZT), Lead lanthanum zirconate titanate (PLZT)], the dielectric constant may **increase as temperature rises**. This behavior is often observed near phase transition temperatures, such as the Curie temperature for ferroelectrics. As the material transitions to a **different phase**, its dielectric constant may change.
- Dielectric Constant Decreases with Temperature:** Many **dielectric** materials exhibit a decrease in their dielectric constant as temperature increases. This is a common behavior in materials like **ceramics and polymers** (water, Silicon dioxide, mica, polystyrene). As the temperature rises, **thermal vibrations** of atoms and molecules **disrupt the alignment of dipoles** within the material, **reducing its ability to store electric charge**.
- Minimal Temperature Dependence:** Some dielectric materials, like certain ceramics and glasses (Polytetrafluoroethylene (PTFE), Alumina (Al<sub>2</sub>O<sub>3</sub>), water, etc), may have minimal temperature dependence over a certain range. These materials are often chosen for applications requiring stable dielectric properties across a broad temperature spectrum.

**Insulating materials :** Materials have **very high electrical resistance** and are used to **prevent or control the flow of electricity** within electrical and electronic systems. Insulating materials are essential for electrical safety, as they help isolate conductive elements and prevent unintended electrical contact. Key characteristics of insulating materials are

- ✓ **High Electrical Resistance:** Insulating materials have a high resistance to the flow of electric current. This property ensures that minimal electrical energy is dissipated as heat within the material.
- ✓ **Electrical Insulation:** The **primary function** of insulating materials is to provide electrical insulation. They are used to separate conductive components in electrical circuits, **preventing short circuits and electrical shocks.**
- ✓ **Thermal Insulation:** Some insulating materials also exhibit good thermal insulation properties. They are used to **reduce heat transfer**, maintain temperature stability, and improve energy efficiency in various applications, including building insulation and refrigeration.

**Types of Insulating Materials:** There is a wide range of insulating materials, including ceramics, plastics (polyethylene, polypropylene, and PVC), rubber, glass, mica, and various composite materials. The choice of material depends on factors like electrical requirements, temperature, and environmental conditions.

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## Applications

- ✓ **Electrical Cables:** Insulating materials are used to cover and protect the conductive cores of electrical cables. Common cable insulation materials include PVC, XLPE (cross-linked polyethylene), and rubber.
- ✓ **Transformers and Capacitors:** Insulating materials are used as dielectric materials in transformers and capacitors to store and manage electrical energy.
- ✓ **Electronics:** In printed circuit boards (PCBs) and electronic devices, insulating materials are used as substrates to support and isolate conductive traces and components.
- ✓ **Building Insulation:** Insulating materials are used in construction to improve energy efficiency by reducing heat transfer through walls, roofs, and floors.
- ✓ **Safety Equipment:** Insulating materials are employed in safety equipment such as electrical gloves and insulating mats to protect individuals working with live electrical components.

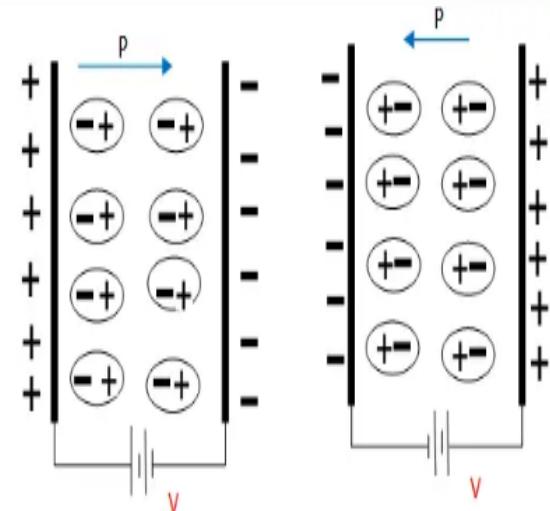
Ferroelectricity is the **ability of the material to have a spontaneous electric polarization**. This polarization can be reversed by the application of an external electric field in the opposite direction.

**Key characteristics of ferroelectric materials include:**

**Spontaneous Polarization:** Ferroelectric materials possess a spontaneous electric polarization that arises when the material's electric dipoles align in a specific direction. This polarization can be reversed when the direction of the applied electric field is changed.

**Hysteresis:** Ferroelectric materials exhibit hysteresis behaviour in their polarization-electric field curves. This means that **even after the applied electric field is removed, the polarization persists until an opposite electric field is applied to reverse it.**

**Phase Transition:** Ferroelectricity is often associated with phase transitions, particularly at a critical temperature called the Curie temperature. Above this temperature, the material may lose its ferroelectric properties and transition to a paraelectric phase.



## Applications:

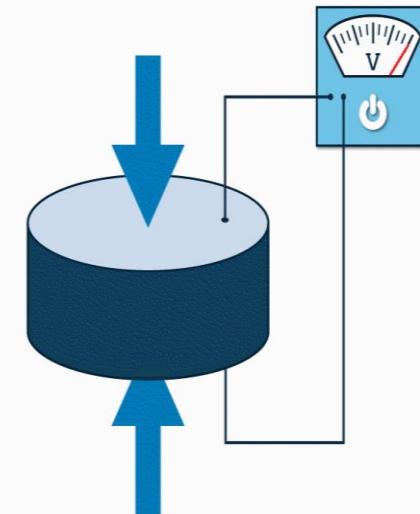
Capacitors,  
piezoelectric devices  
(sensors and actuators),  
non-volatile memory  
(ferroelectric RAM),  
and sensors for thermal  
imaging and sound.

Piezoelectric materials produce an electrical field when subject to a mechanical strain. Conversely, if an electrical field is applied to them, the material is stressed.

**Direct Piezoelectric Effect:** When mechanical stress is applied to a piezoelectric material, it causes a displacement of electric charges within the material, resulting in the generation of an electric voltage. This effect is utilized in piezoelectric sensors, actuators, and transducers.

**Inverse Piezoelectric Effect:** When an electric field is applied to a piezoelectric material, it induces mechanical strain or deformation in the material. This effect is exploited in piezoelectric actuators, such as those used in inkjet printers, ultrasonic devices, and precision positioning systems.

**Applications :** sensors ( in touchscreens and accelerometers), ultrasound transducers, energy harvesting devices (generating electricity from mechanical vibrations), musical instruments such as electric guitars, remote control, nebulizers



A **superconductor** is a material that can conduct electricity without any resistance when cooled below a certain temperature, known as its **critical temperature**.

## Key Properties of Superconductors

**1. Zero Electrical Resistance**

**2. Magnetic Field Expulsion (Meissner Effect):** Superconductors expel magnetic fields from their interior, causing phenomena like magnetic levitation.

**3. Critical Parameters:** Superconductors function only under specific conditions:

1. Below their critical temperature.
2. Below a critical magnetic field strength.
3. Below a critical current density.

## Types of Superconductors

**1. Type-I Superconductors:** Pure elements (e.g., lead, mercury) that exhibit superconductivity and are fully diamagnetic below their critical temperature.

**2. Type-II Superconductors:** Materials (e.g., niobium-titanium alloys) that allow partial magnetic field penetration, often used in high-performance applications.

## Applications

Magnetic Levitation  
MRI Machines  
Particle Accelerators  
Quantum Computing  
Power Grids



# Optical Properties

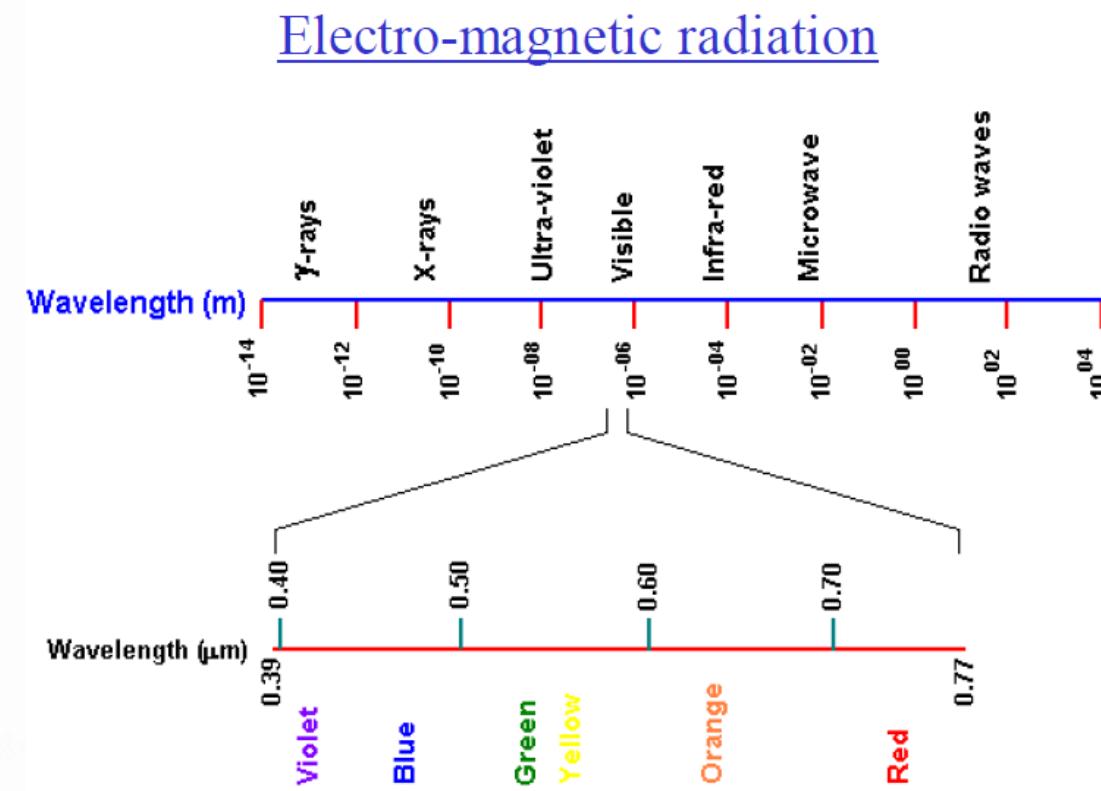
# Optical Properties

The **optical properties** of materials describe how they interact with electromagnetic radiation, particularly visible light.

These properties depend on the material's composition, structure, and how light interacts with its electrons and atoms.

Electromagnetic spectrum of radiation spans the wide range from  $\lambda$ - rays with wavelength as

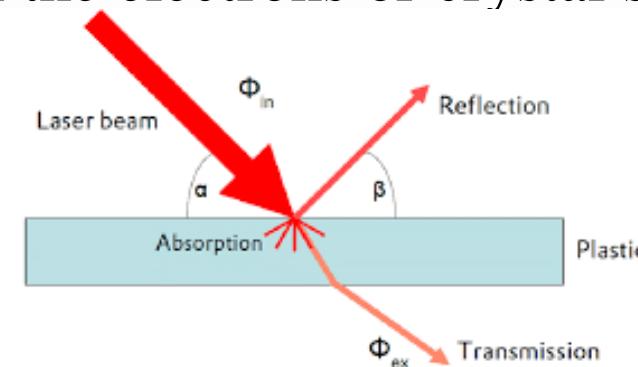
$10^{-12}$  m through x-rays, ultraviolet, visible, infrared and finally radio waves with wavelengths as long as  $10^5$  m.



Visible light is one form of electromagnetic radiation with wavelengths ranging from 0.39 to 0.77  $\mu\text{m}$ . Light can be considered as having waves and consisting of particles called photons.  $E = hv = hc_0/\lambda$

Interaction of photons with the electrons or crystal structure of a material, leads to a following phenomena

- Absorption
- Reflection
- Transmission
- Refraction



At any instance of light interaction with a material, the total intensity of the incident light striking a surface is equal to sum of the absorbed, reflected and transmitted intensities i.e.  $I_0 = I_A + I_R + I_T$

Materials are **classified** on the basis of their interaction with visible light into three categories.

- **Transparent materials:** Materials that are capable of transmitting light with relatively little absorption and reflection are called *transparent materials* i.e. we can see through them.
- **Translucent materials:** Materials through which light is transmitted diffusely i.e. objects are not clearly distinguishable when viewed through.
- **Opaque materials:** Materials that are impervious to the transmission of visible light are termed as *opaque materials*.

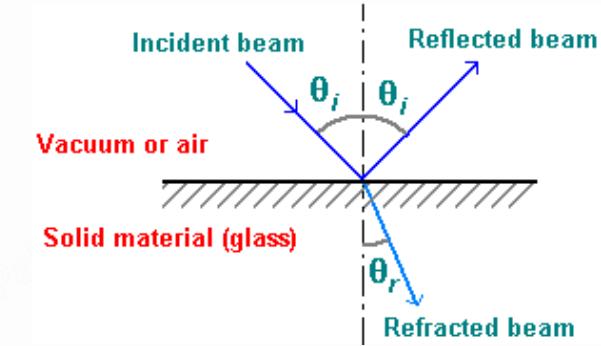
## Metals – Optical Properties

Metals consist partially filled high-energy conduction bands. When photons are directed at metals, their energy is used to excite electrons into unoccupied states. Thus metals are opaque to the visible light. Metals are, however, transparent to high end frequencies i.e. x-rays and  $\gamma$ -rays.

Absorption of takes place in very thin outer layer. Thus, metallic films thinner than  $0.1 \mu\text{m}$  can transmit the light. The absorbed radiation is emitted from the metallic surface in the form of visible light of the same wavelength as reflected light. The reflectivity of metals is about 0.95.

$$n = \frac{c_0}{c}$$

$$n = \frac{\sin \theta_i}{\sin \theta_r}$$



## Non-Metals – Optical Properties

Non-metallic materials consist of various energy band structures. when light photons are transmitted through a material, they causes polarization of the electrons and in-turn the speed of light is reduced and the beam of light changes direction.

**Luminescence** : It is the process where a material absorbs energy and then immediately emits visible or near-visible radiation. It consists of electron excitation and then dropping down to lower energy states.

If the emission of radiation occurs within  $10^{-8}$  seconds after excitation, the luminescence is called **fluorescence**, and if it takes longer than  $10^{-8}$  seconds, it is known as **phosphorescence**.

Ordinarily pure materials do not display this phenomenon. Special materials called *phosphors* have the capability of absorbing high-energy radiation and spontaneously emitting lower-energy radiation. Ex.: some sulfides, oxides, tungstates, and few organic materials.

**Based on source for electron excitation**, luminescence is three types: photo-luminescence, cathode-luminescence, and electro-luminescence.

- **Photo-luminescence**: occurs in fluorescent lamps. Here ultra-violet radiation from low-pressure mercury arc is converted to visible light by calcium halo-phosphate phosphor ( $\text{Ca}_{10}\text{F}_2\text{P}_6\text{O}_{24}$ ). In commercial lamps, about 20% of  $\text{F}^-$  ions are replaced with  $\text{Cl}^-$  ions.
- **Cathode-luminescence**: is produced by an **energized cathode** which generates a beam of high-energy bombarding electrons. Ex: Applications of this include electron microscope; cathode-ray oscilloscope; color television screens.
- **Electro-luminescence**: occurs in devices with **p-n rectifying junctions** which are stimulated by an externally applied voltage. When a forward biased voltage is applied across the device, electrons and holes recombine at the junction and emit photons in the visible range (mono-chromatic light i.e. single color). These diodes are called light emitting diodes (LEDs).

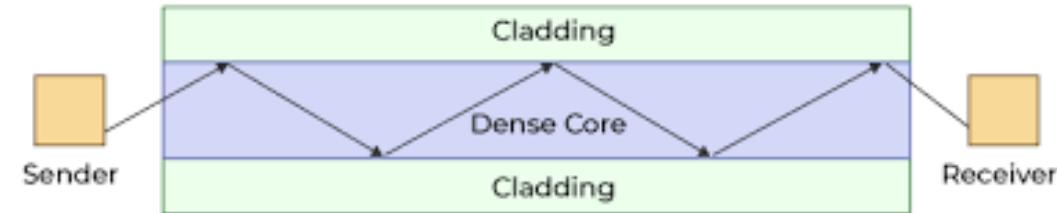
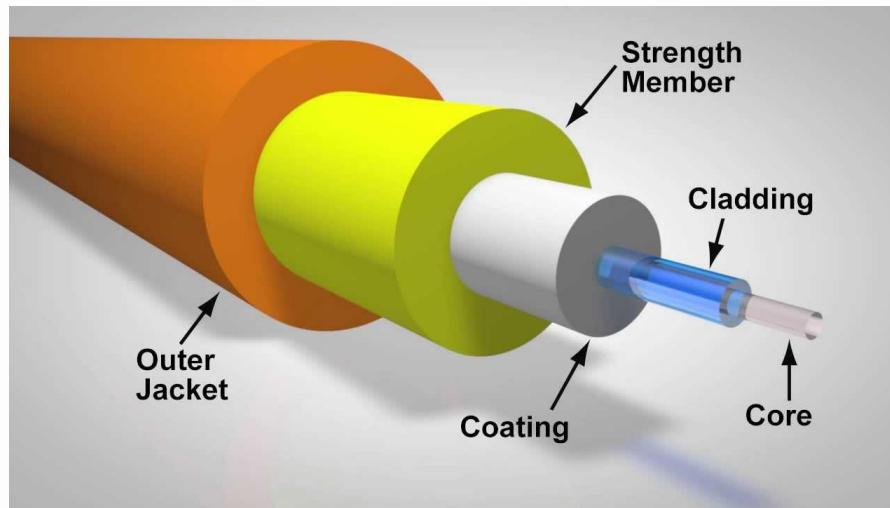
The **optical fibre** is a device which works on the principle of total internal reflection by which light signals can be transmitted from one place to another with a negligible loss of energy.



## Characteristics of Optical Fibre:

- It has a large bandwidth. Thus optical fibres have greater information carrying capacity due to greater bandwidth.
- In optical fibre system transmission losses are very low.
- Optical fibres are of small size and have lightweight as compared to electrical cables. They are flexible and very high tensile strength. Thus they can be twisted and bent easily.
- Optical fibres provide a high degree of signal security as it is confined to the inside of fibre and cannot be tapped and tempered easily. Thus it satisfies the need for security which is required in banking and defence.
- Optical fibre communication is free from electromagnetic interference.
- Fibre optic fibres do not carry high voltages or current. Hence, they are safer than electrical cables.

**Construction :** It consists of a very thin fibre of silica or glass or plastic of high refractive index called the **core**. The core has a diameter of  $10 \mu\text{m}$  to  $100 \mu\text{m}$ . The core is enclosed by a cover of glass or plastic called **cladding**. **The refractive index of the cladding is less than that of the core** (which is must condition for the working of the optical fibre). The difference between the two indices is very small of order  $10^{-3}$ . The core and the cladding are enclosed in an outer protective **jacket** made of plastic to provide strength to the optical fibre. The refractive index can change from core to cladding abruptly (as in step index fibre) or gradually (as in graded index fibre).



Optical fiber work on the principle of **total internal reflection**. With light, the refractive index is listed. The angle of refraction at the interface between two media is governed by Snell's law.

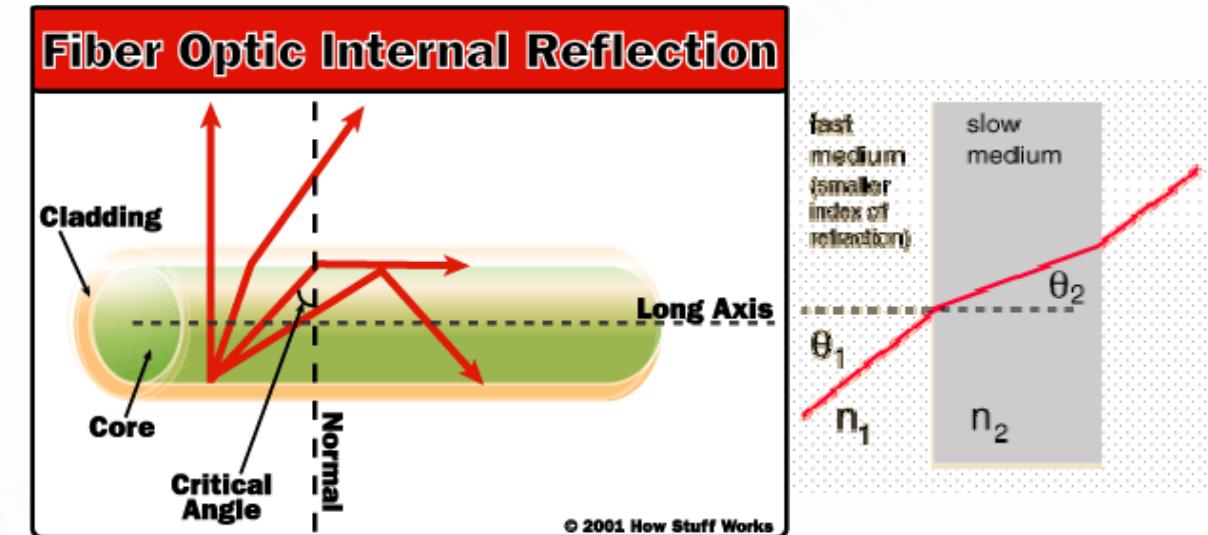
Snell's Law

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

where  $n_1$  and  $n_2$  are refractive indices and  $\theta_1$  and  $\theta_2$  are incident angle of light of respective media.

**Critical angle:** Angle of incidence at which angle of refraction =  $90^0$ . If the angle of incidence is greater than the critical angle, total internal reflection occurs, causing the light to be reflected back into the core. The critical angle is determined by the refractive indices of the core ( $\mu_1$ ) and cladding ( $\mu_2$ ) using the formula:  $\theta_c = \sin^{-1}(\mu_2/\mu_1)$ .

Let  $\mu_{\text{air}}$ ,  $\mu_{\text{core}}$  and  $\mu_{\text{cladding}}$  be the refractive indices of air, core and cladding respectively. For total internal reflection  $\mu_{\text{core}} > \mu_{\text{cladding}} > \mu_{\text{air}}$  relation should be followed.



$$\mu_{\text{core}} > \mu_{\text{cladding}} > \mu_{\text{air}} \cdot$$



# Mechanical Properties

Materials, in service, are subjected to forces or loads. The mechanical behaviour of a material reflects the relationship between its response or deformation to an applied load or force.

Mechanical forces can be broadly categorized into tension, compression, shear, torsion, and bending.

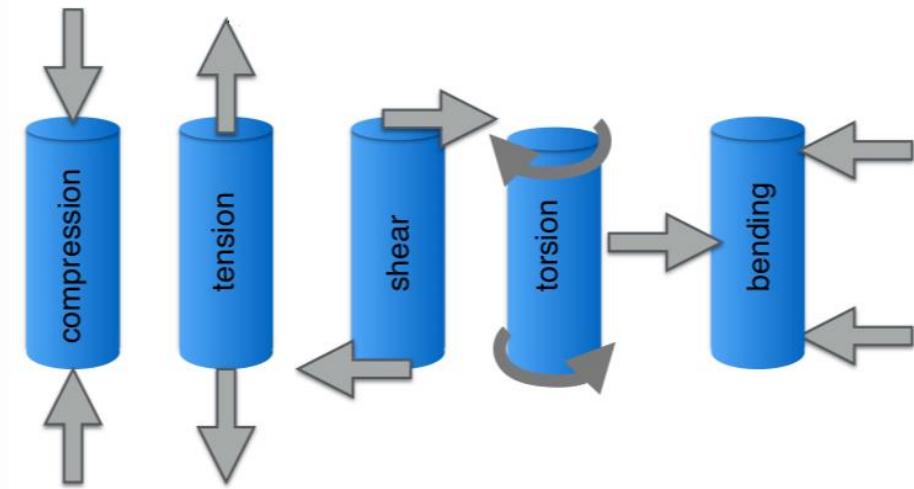
**Tension:** Equal axial forces that pulls or stretches an object, causing it to elongate.

**Compression:** Equal axial forces that pushes or squeezes an object, causing it to shorten or deform.

**Shear:** Equal non – axial forces that causes different layers of a material to slide past each other.

**Torsion:** A twisting force that causes a material to rotate around its axis.

**Bending:** A force that causes a material to deform or curve under the influence of a load.



One of the most common mechanical stress–strain tests is performed in *tension*. A specimen is deformed, usually to fracture, with a gradually increasing tensile load that is applied uniaxially along the long axis of a specimen. A standard tensile specimen is shown in Figure. Normally, the cross section is circular, **Stress ( $\sigma$ )** defined as force per unit area. Stress measures the internal resistance of a material to an applied force. The unit commonly used is Mega Pascal( $MN/m^2$ ) or  $10^6 N/m^2$  which is numerically equal to  $N/mm^2$ .

**Strain ( $\epsilon$ )** The relative deformation of a material in response to stress. It is the ratio of the change in length to the original length..

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

$$\epsilon = \frac{l_i - l_0}{l_0} = \frac{\Delta l}{l_0}$$

Where,  $F$  is the instantaneous load applied perpendicular to the specimen cross section in units of newtons (N).  $A_0$  is the original cross sectional area before any load is applied ( $m^2$ ).  $l_0$  is the original length before any load is applied, and  $l_i$  is the instantaneous length. Engineering strain is unitless.

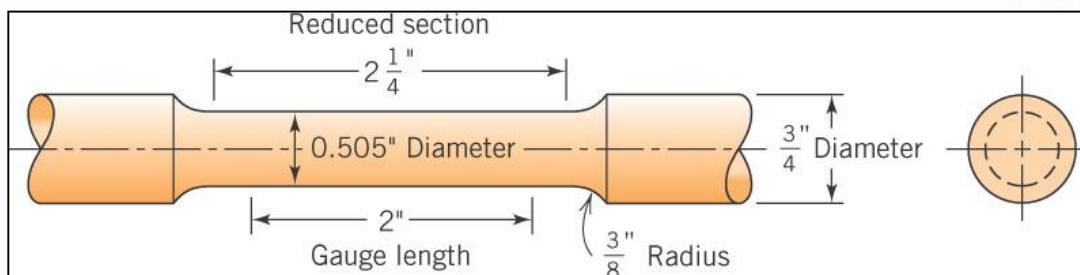
# Stress-strain Diagram

Go, change the world

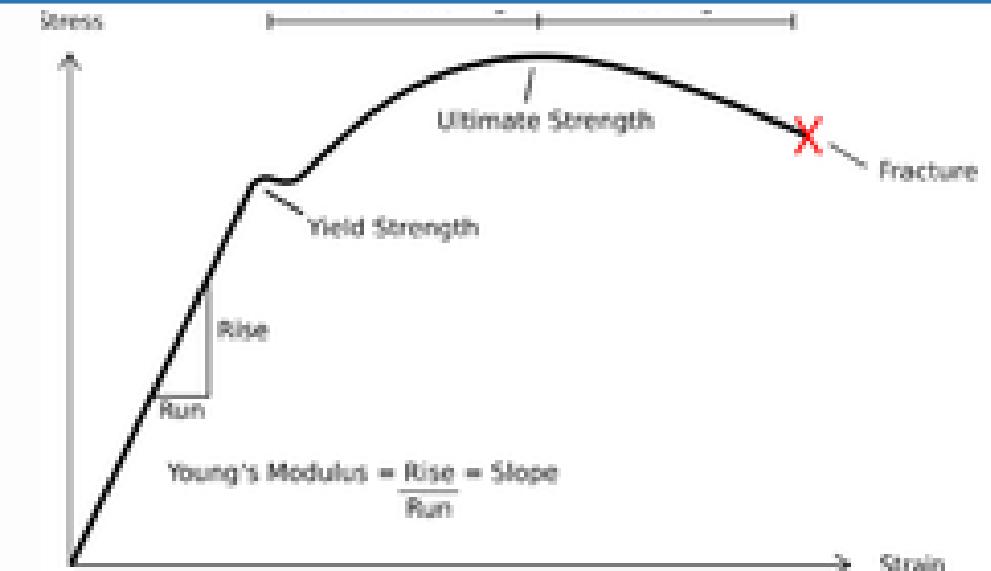
The stress and strain experienced by a material under an external load is represented by a stress – strain diagram.

A specimen is deformed, usually to fracture, with a gradually increasing tensile load that is applied uniaxially along the long axis of a specimen. A standard tensile specimen is shown in Figure. Normally, the cross section is circular.

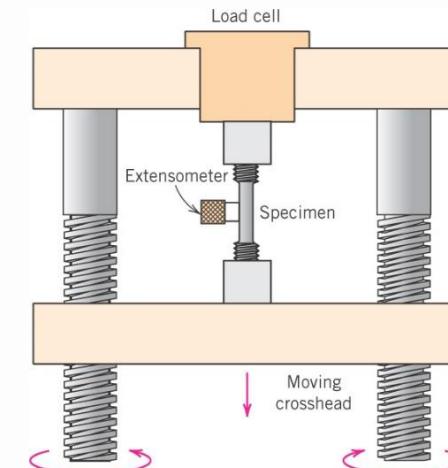
A typical stress-strain curve for a ductile material is shown in figure.



Standard tensile specimen



Typical stress-strain curve for a ductile material



Universal Testing Machine

# Stress-strain Diagram

Go, change the world

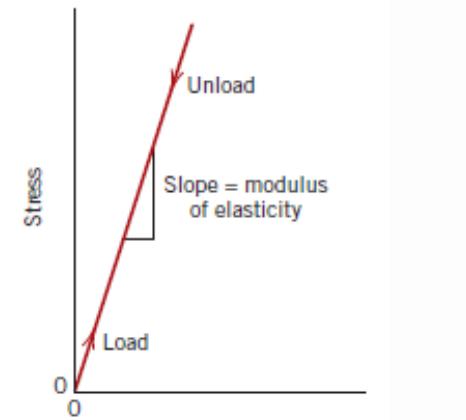
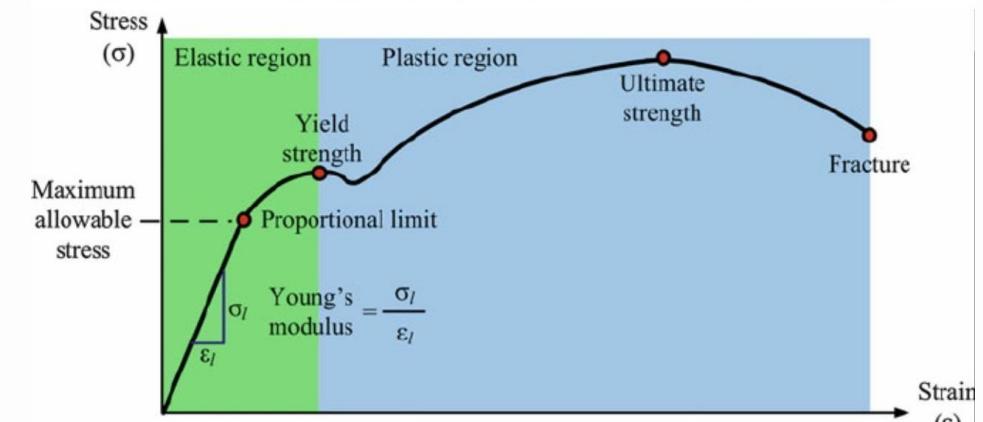
The plot represents the tensile behaviour. It is usually plotted using stress (applied load / original cross sectional area) on the y-axis and strain (change in length / original gauge length) on the x-axis.

The initial portion of the curve will be linear, representing the **elastic behaviour** (obeying Hooke's law, green in colour), beyond which a non-linear region representing **plastic behaviour** (blue in colour)

Deformation in which stress and strain are proportional is called **elastic deformation**. The elastic properties are **stiffness, elastic strength and resilience**.

**Stiffness** : In the stress-strain diagram, the slope of the linear segment corresponds to the **modulus of elasticity E**. This modulus is known as **stiffness**, or a material's resistance to elastic deformation.

The greater the modulus, the stiffer the material, or the smaller the elastic strain that results from the application of a given stress. The modulus is an important design parameter used for computing elastic deflections.



Schematic stress-strain diagram showing linear elastic deformation for loading and unloading cycles.

Strains (degree to which a structure deforms) depends on the magnitude of an imposed stress.

For most metals that are stressed in tension and at relatively low levels, stress and strain are proportional to each other through the relationship

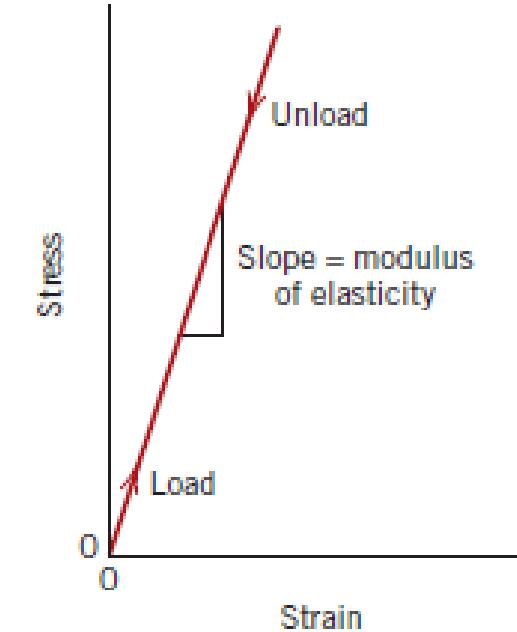
$$\sigma = E\epsilon$$

This is known as **Hooke's law**, and the constant of proportionality E (GPa or psi)<sup>6</sup> is the **modulus of elasticity**, or **Young's modulus**. Young's Modulus is measure of stiffness of the material.

Modulus of elasticity values for several metals at room temperature are presented in Table.

Metal Alloy	Modulus of Elasticity	
	GPa	$10^6$ psi
Aluminum	69	10
Brass	97	14
Copper	110	16
Magnesium	45	6.5
Nickel	207	30
Steel	207	30
Titanium	107	15.5
Tungsten	407	59

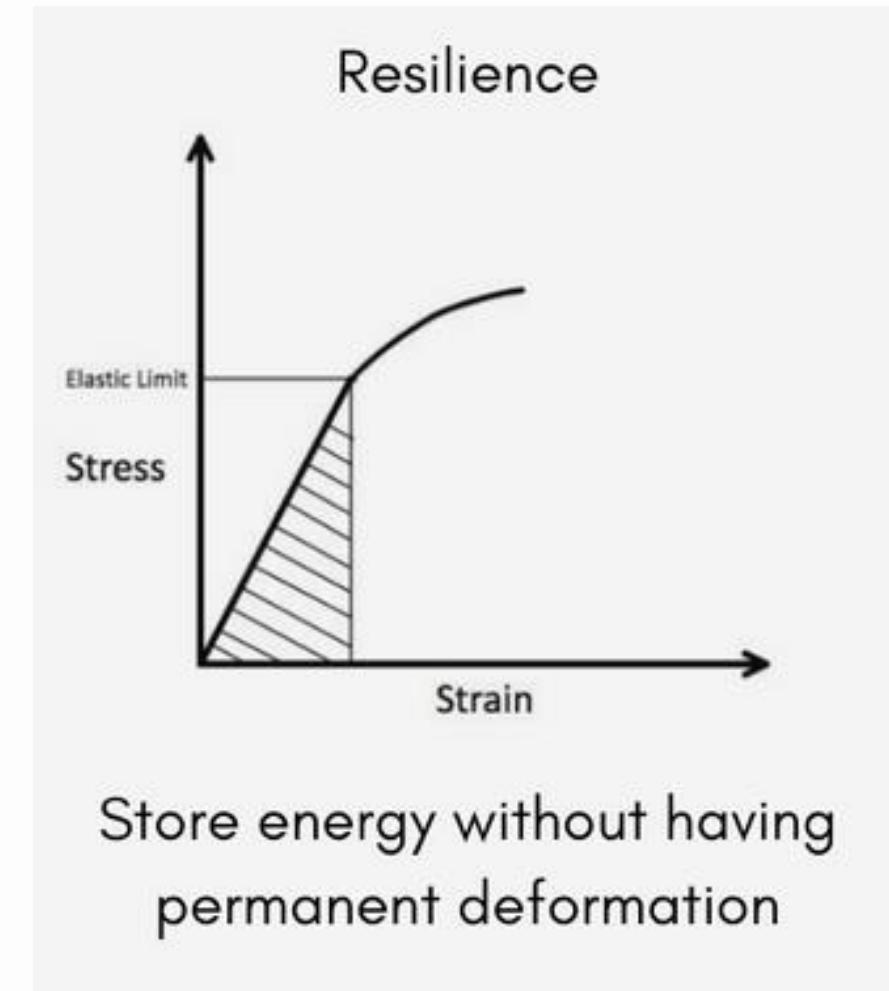
Modulus of elasticity values for several metals at room temperature



Schematic stress-strain diagram showing linear elastic deformation for loading and unloading cycles.

**Elastic Strength**, also known as the elastic limit or yield strength, refers to the maximum stress a material can withstand before it undergoes permanent plastic deformation. Within this limit, the material will return to its original shape when the stress is removed. Elastic limit is marked in stress – stain diagram in the figure.

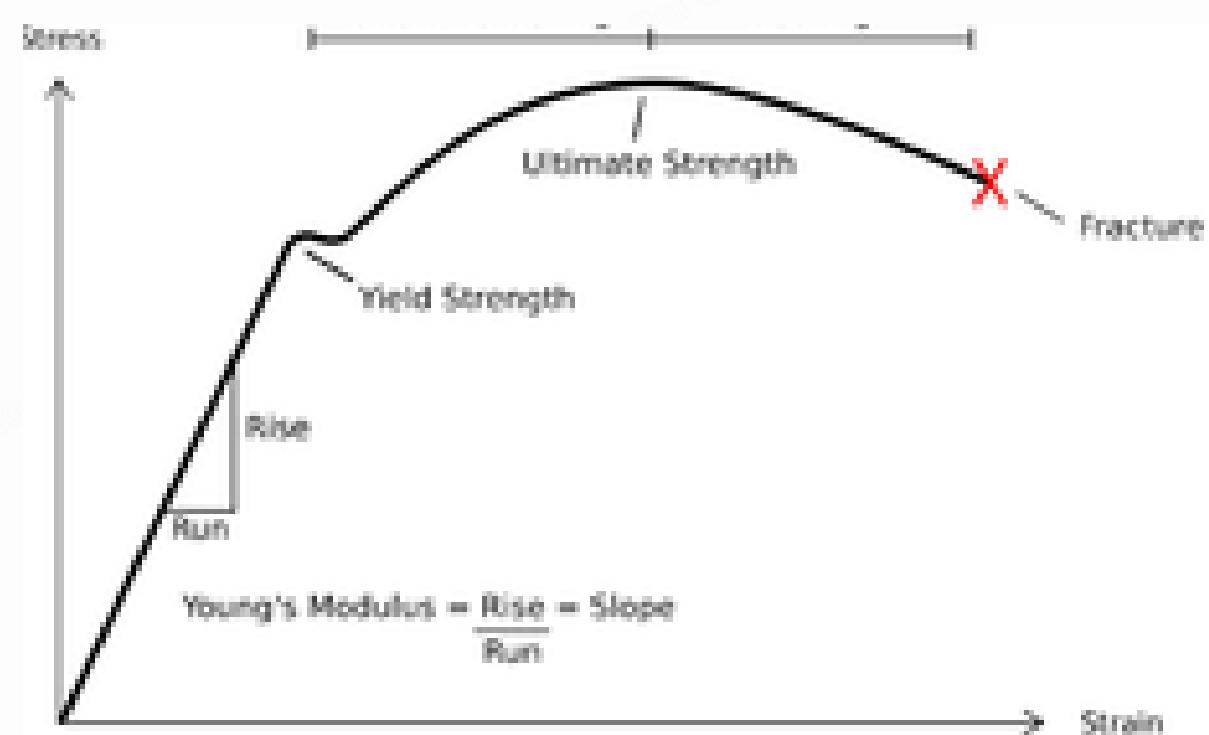
**Resilience** is the capacity of a material to absorb energy when it is deformed elastically and then, upon unloading, to have this energy recovered. The associated property is the **modulus of resilience**,  $U_r$  which is the strain energy per unit volume required to stress a material from an unloaded state up to the point of yielding. The modulus of resilience for a specimen subjected to a uniaxial tension test is the area under the engineering stress-strain curve taken to yielding (shown by shaded area in figure).



Beyond the elastic limit of a material, the Hooke's law is not valid. For a stress beyond the elastic limit, a permanent and non-recoverable deformation takes place. This is termed as plastic behaviour. The properties are yield strength, ultimate tensile strength, fracture strength, ductility and toughness.

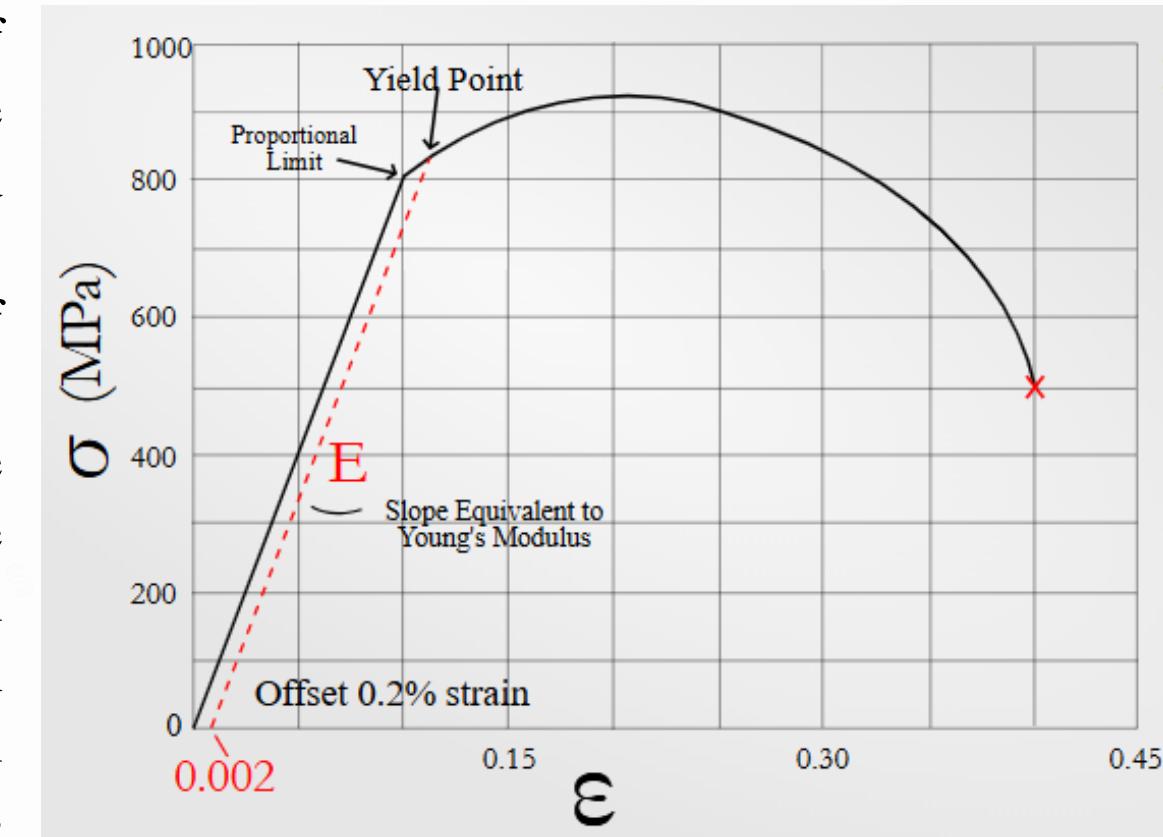
**Yield strength** : The stress at which permanent (plastic) deformation or yielding start to occur is known as yield strength. It is a measure of the resistance to plastic deformation.

Yield strength can be determined by proportionality limit and offset yield strength



**Proportional limit :** For most metals that experience this gradual elastic–plastic transition, the point of yielding may be determined as the initial departure from linearity of the stress–strain curve. This is called the **proportional limit**.

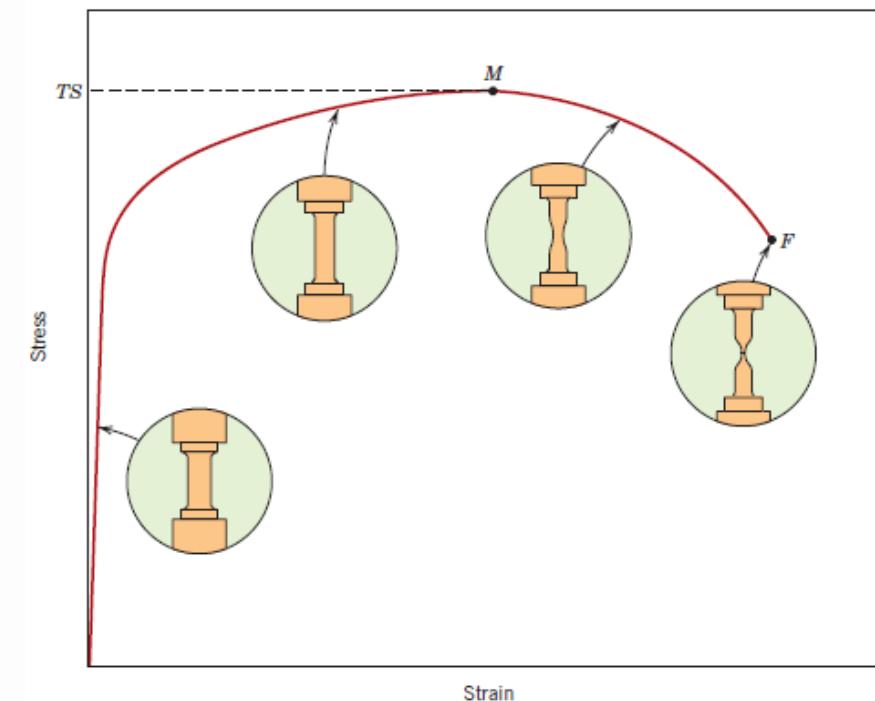
**Offset yield strength :** In many cases the point of proportionality limit may not be determined precisely. In this method a straight line is drawn parallel to the elastic portion of the stress–strain curve at some specified strain offset, usually 0.2% of the failure strain (i.e 0.002 strain). The corresponding stress at which this offset line meets the stress – strain curve is taken as the yield strength of the material. The strength is termed as offset yield strength or the proof stress. The units of yield strength are in MPa or psi.



Proportionality limit and offset yield strength

**Ultimate Tensile strength :** After yielding, the stress necessary to continue plastic deformation in metals increases to a maximum, and then decreases to the eventual fracture. The Ultimate tensile strength UTS (MPa or psi) is the stress at the maximum on the engineering stress–strain curve. This corresponds to the maximum stress (point M in the figure) that can be sustained by a structure in tension. If this stress is applied and maintained, the material deforms and fracture takes place without any further increase in load.

In tensile specimens, up to the ultimate load, uniform deformation takes place in the narrow region. However, at this maximum stress, a small constriction or neck begins to form at some point in the central region, and the further deformation up to failure is restricted only to the necked portion. This phenomenon is termed as “necking,” and shown in figure. Tensile strengths may vary from 50 MPa (7000 psi) for an aluminum to 3000 MPa (450,000 psi) for the high-strength steels.



Typical engineering stress–strain behavior to fracture, point F. The tensile strength UTS is indicated at point M.

**Fracture strength :** Once the load cross the ultimate stress value, it drops gradually at a stress, at which the specimen fractures (Point E in Figure). The stress at which the fracture of the specimen takes place is termed the fracture strength.

**Ductility :** It is a measure of the degree of plastic deformation take place till the material fails.

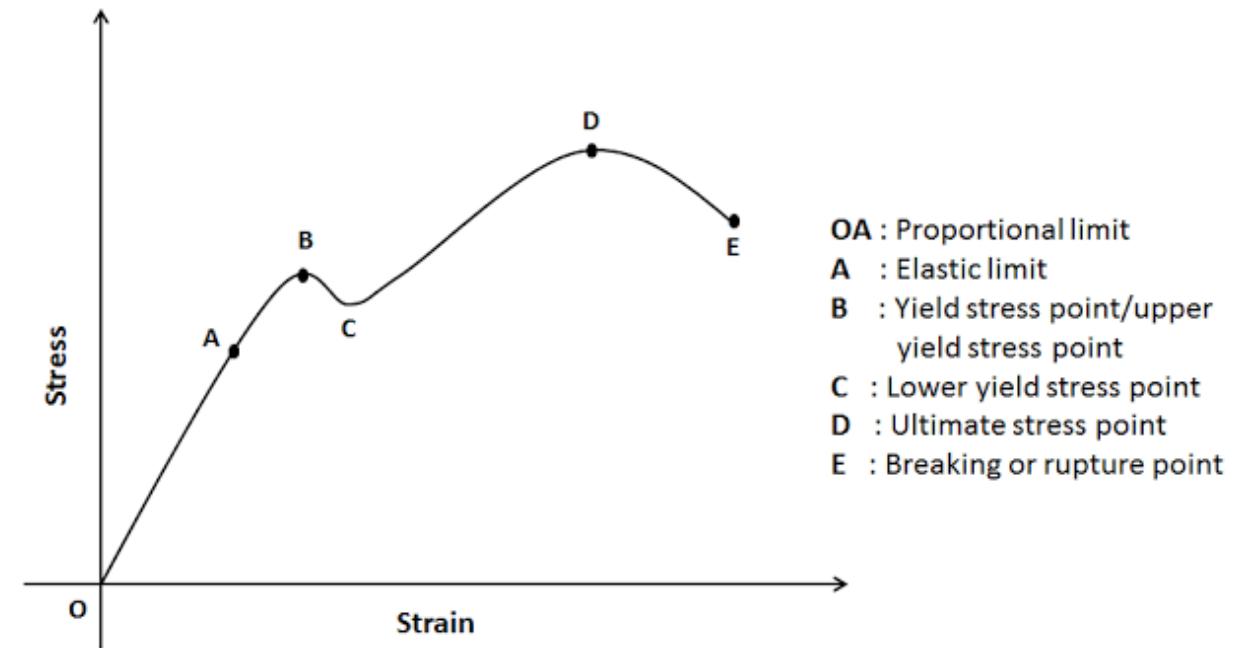
A material that experiences very little or no plastic deformation upon fracture is termed brittle.

Ductility may be expressed quantitatively as either **percent elongation or percent reduction in area**.

The percent elongation %EL is the percentage of plastic strain at fracture. Percent elongation or percent reduction in area is calculated according to the equations given below.

$$\% \text{EL} = \left( \frac{l_f - l_0}{l_0} \right) \times 100$$

$$\% \text{RA} = \left( \frac{A_0 - A_f}{A_0} \right) \times 100$$

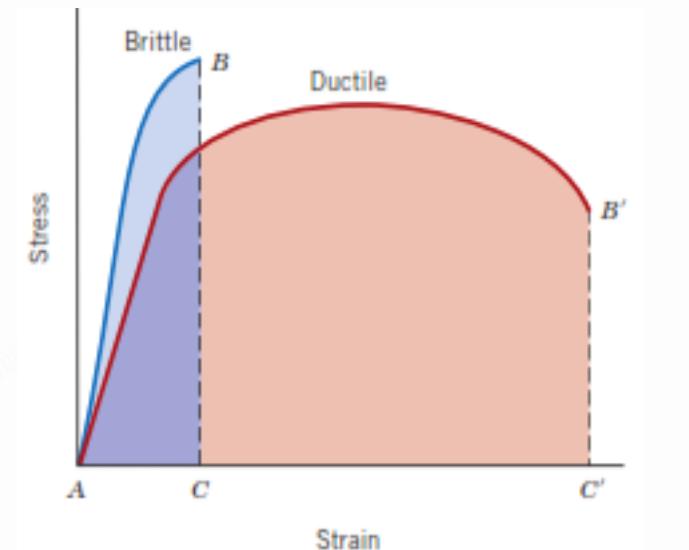


where  $l_f$  is the fracture length and  $l_0$  is the original gauge length as above.

where  $A_0$  is the original area of cross section and  $A_f$  is the area of cross section at the point of fracture

**Toughness :** It is a measure of the ability of a material to absorb energy up to fracture both in elastic and plastic range. Thus the total area under the curve up to the point of fracture represents the toughness of a material.

That means, higher the plastic deformation, higher is the toughness of the material. Brittle materials have very low toughness. The shaded area under the stress strain curve of given figure shows toughness of brittle and ductile materials.



**Fracture:** The separation of a solid body into two or more pieces under the applied stress, at temperatures below the melting point is termed fracture.

Steps in fracture:

- crack formation
- crack propagation

## Types of Fracture

Macroscopic level : Ductile fracture or brittle fracture

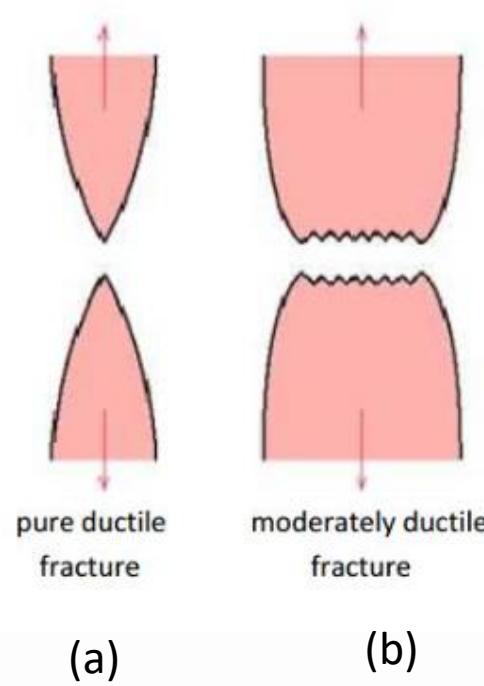
Macroscopic level : Trans-granular fracture and Inter – granular fracture

**Ductile fracture** – In a ductile fracture the material undergoes a considerable amount of plastic deformation. When the applied stress exceeds a critical value, crack forms indicating the beginning of failure process. In the ductile materials, the crack propagation is slow. It resists further deformation unless there is an increase in the applied stress (Crack is stable). Thus, a ductile fracture is always accompanied with extensive deformation around the crack region. Ductile fracture is preferred in most applications. Macroscopic fracture profiles of ductile fracture are shown in figure.

**Highly (pure) ductile materials**, undergo deformation such that their fracture surfaces neck down almost to a point i.e almost 100 % reduction in area shown in figure (a). It is observed for pure soft metals (e.g. Pb, Au, Cu) at room temperature, other metals, polymers, glasses at high temperature.

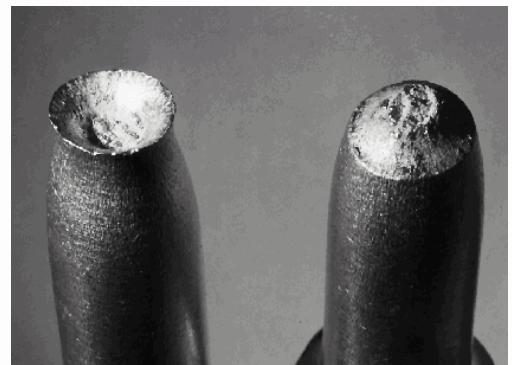
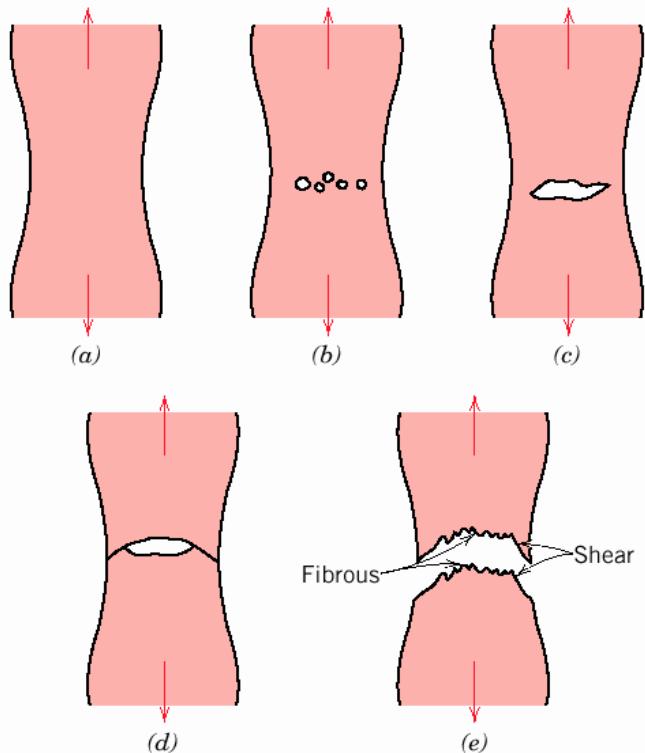
**Moderately ductile materials** : In most common ductile materials, in tension the fracture accompanied by a moderate amount of plastic deformation and necking. This leads to a fracture surface as shown in figure (b). Such a fracture is popularly known as cup-and-cone fracture.

At microscopic level, central region of the fractured surface shows an irregular and fibrous structure due to plastic deformation.



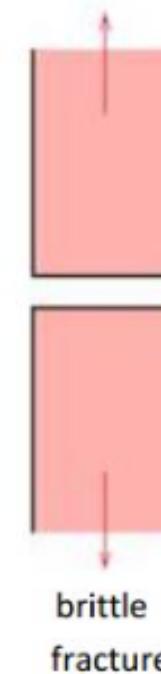
## Stages in ductile fracture

1. **Necking** : As the applied stress exceeds, the yield stress, necking (reduced cross section) takes place and material yields (plastic deformation) by a considerable amount. Figure (a)
2. **Formation of cavities** : After necking, small cavities (or micro-voids) form within the necked region. Figure (b)
3. **Coalescence of cavities and formation of crack** : With increasing stress, gradually the cavities enlarge, join together and coalesce to form a crack roughly perpendicular to the axis of applied stress. Figure (c)
4. **Crack propagation** : Further, the crack propagates under increasing stress, with more and more cavities coalescing with it. Figure (d)
5. **Final Fracture** : As the crack propagates, and approaches the surface of the neck, it changes its direction to  $45^0$  (shear stress is maximum at  $45^0$  to the applied stress) to the tensile stress axis and fracture by shear deformation. This results in the formation of cup-and-cone fracture. Figure (e)



**Brittle fracture** – Brittle fracture is one which takes place without considerable plastic deformation and leads to the catastrophic failures (crack is “unstable”). In this, crack propagation does not come across any resistance to its growth ( due to absence of plastic deformation), hence the crack growth is rapid. Crack propagates nearly perpendicular to the direction of the applied stress and produces almost a flat fracture surface shown in figures. This type of fracture can be observed in ceramics, ice, cold metals.

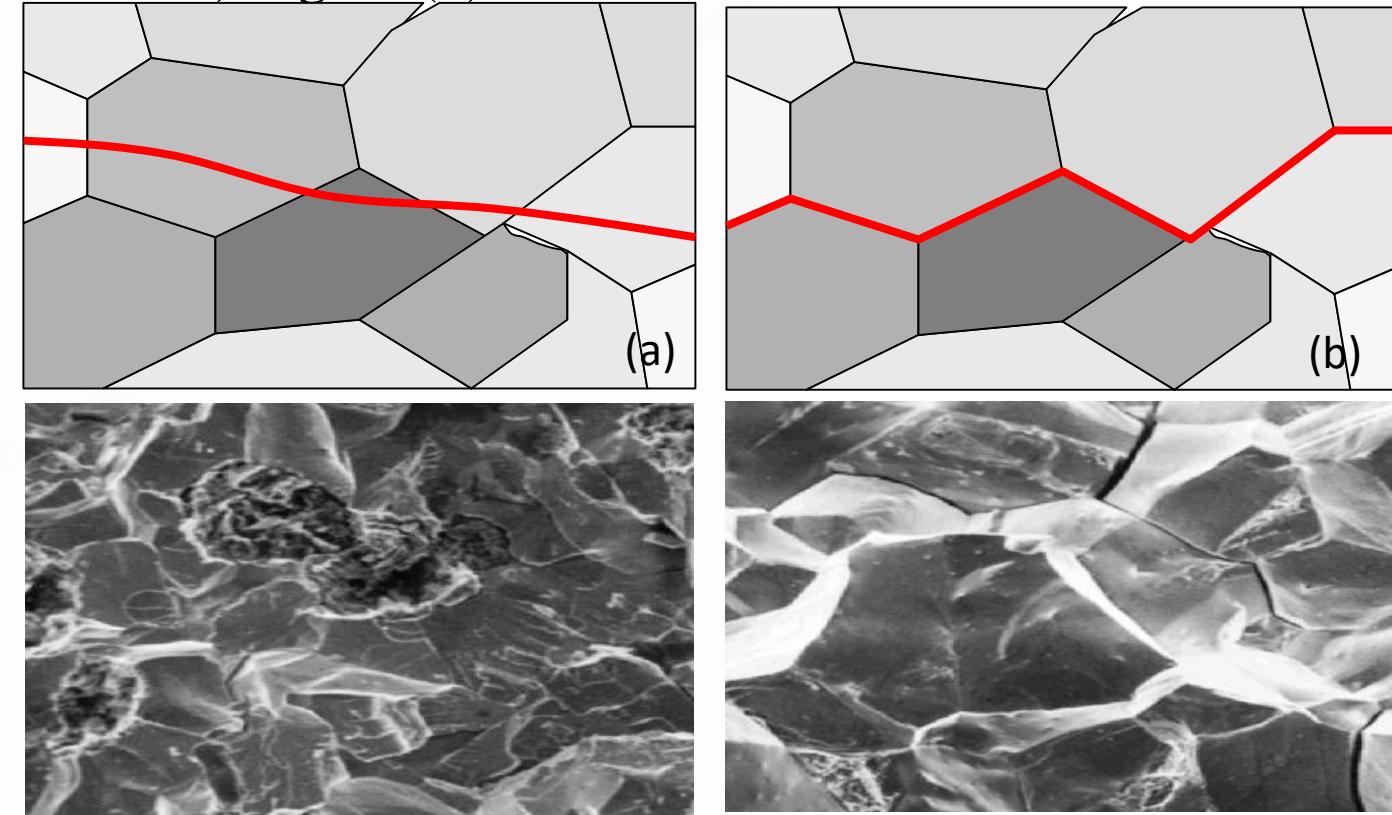
Brittle fracture usually occurs along specific crystallographic planes, called cleavage planes, that are perpendicular to the applied stress.



Brittle fracture can be either trans-granular (intra-granular) fracture and inter – granular fracture.

**Trans granular fracture:** Fracture cracks pass through grains. Fracture surface have faceted texture because of different orientation of cleavage planes in grains. Figure (a)

**Inter-granular fracture:** Fracture crack propagation is along grain boundaries (grain boundaries are weakened or embrittled by impurities segregation etc.) Figure (b)



As the temperature is lowered, the impact energy drops suddenly over a relatively narrow temperature range, below which the energy has a constant but small value, that is, the mode of fracture is brittle.

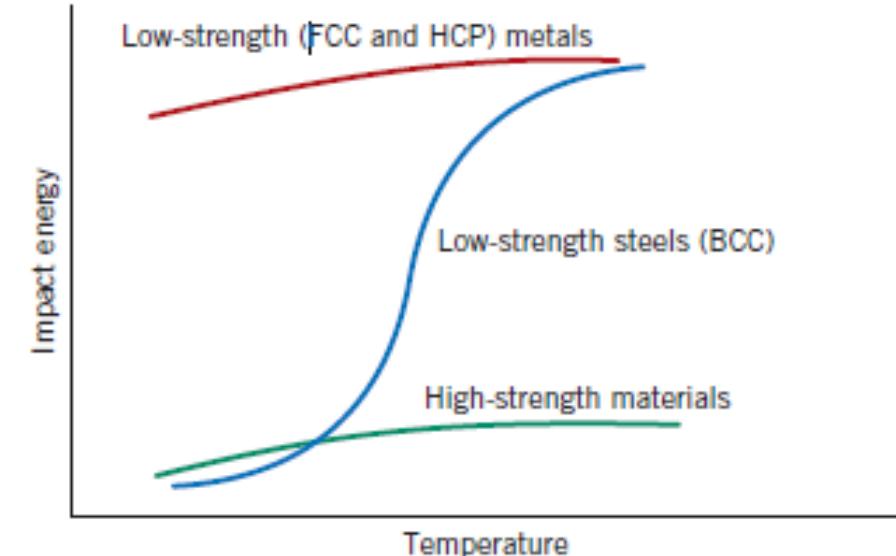
The **ductile-to-brittle transition temperature (DBTT)** is the temperature at which a material's fracture behavior transitions from predominantly ductile to brittle.

This transition is influenced by factors like material composition, temperature, and strain rate.

The range of temperatures over which the ductile-to-brittle transition occurs for many alloys is shown in the figure.

**Applications:** Understanding the DBTT is crucial in engineering, as it helps determine if a material will remain ductile and impact-resistant at low temperatures, particularly in applications like construction, transportation, and manufacturing.

Structures constructed from alloys that exhibit this ductile-to-brittle behaviour should be used only at temperatures above the transition temperature, to avoid brittle and catastrophic failure.



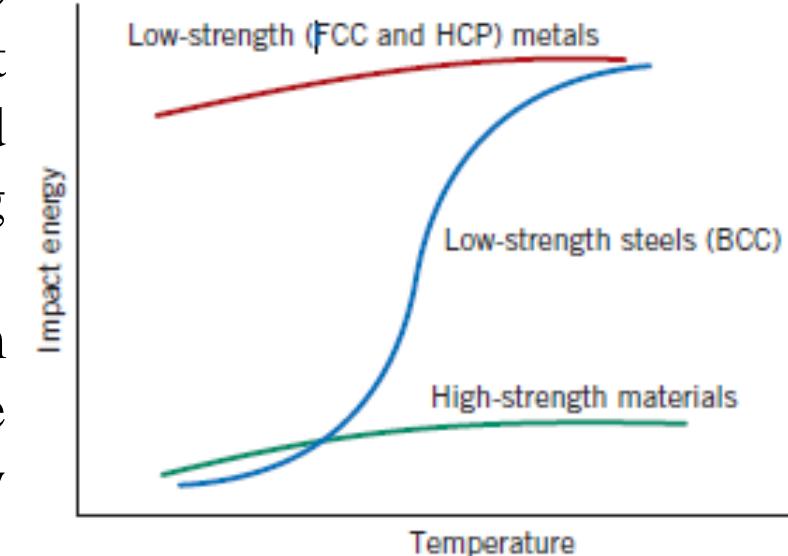
Schematic curves for three general types of impact energy versus temperature behaviour

It may be noted from the figure that, low-strength FCC metals (some aluminum and copper alloys) and most HCP metals do not experience a ductile-to-brittle transition (**upper curve** of figure), and retain high impact energies (i.e., remain ductile) with decreasing temperature.

For high-strength materials (e.g., high-strength steels and titanium alloys), the impact energy is also relatively insensitive to temperature (**the lower curve** of figure), however, these materials are also very brittle, as reflected by their low impact energy values.

The characteristic ductile-to-brittle transition is represented by the **middle curve** of figure. This behaviour is typically found in low-strength steels that have the BCC crystal structure. For these low-strength steels, the transition temperature is sensitive to both alloy composition and microstructure.

Most **ceramics and polymers** also experience a ductile-to-brittle transition. For **ceramic** materials, the transition occurs only at elevated temperatures, ordinarily in excess of  $1000^{\circ}\text{C}$ . **Polymers** experience a ductile-to-brittle transition over a relatively narrow temperature range.



Classic examples of this type of failure occurred, with disastrous consequences, during World War II when a number of welded transport ships, away from combat, suddenly and precipitously split in half. The vessels were constructed of a steel alloy that possessed adequate ductility according to room-temperature tensile tests. The brittle fractures occurred at relatively low ambient temperatures, at about in the vicinity of the transition temperature of the alloy. Each fracture crack originated at some point of stress concentration, probably a sharp corner or fabrication defect, and then propagated around the entire girth of the ship.

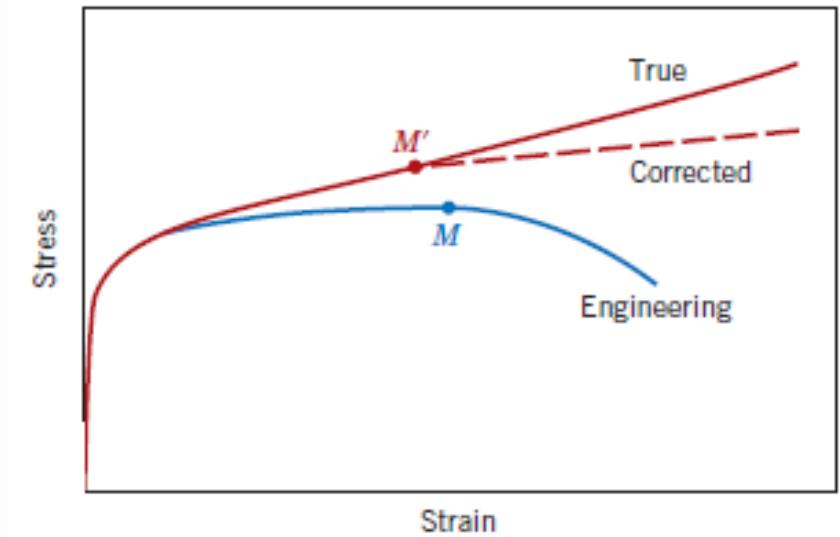


Failure at WWII ships

From stress strain curve, the decline in the stress necessary to continue deformation past the maximum, point  $M$ , seems to indicate that the metal is becoming weaker. This is not at all the case; as a matter of fact, it is increasing in strength. However, the cross-sectional area is decreasing rapidly within the neck region, where deformation is occurring. This results in a reduction in the load-bearing capacity of the specimen. The stress, as computed, is on the basis of the original cross sectional area before any deformation, and does not take into account this reduction in area at the neck. Sometimes it is more meaningful to use a **true stress–true strain** scheme. **True stress** ( $\sigma_t$ ) is defined as the load  $F$  divided by the instantaneous cross-sectional area  $A_i$  over which deformation is occurring. Furthermore, it is occasionally more convenient to represent strain as **true strain** ( $\varepsilon_t$ ).

$$\sigma_t = F/A_i \text{ and } \varepsilon_t = \ln(l_0/l_i)$$

True stress and strain should be computed from actual load, cross-sectional area, and gauge length measurements. A schematic comparison of engineering and true stress–strain behaviours is made in Figure. It is worth noting that the true stress necessary to sustain increasing strain continues to rise past the tensile point  $M'$ .

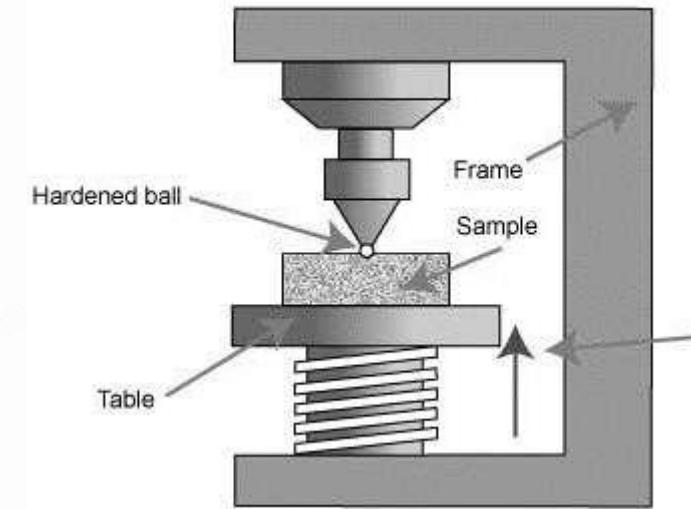


**Hardness** is a measure of a material's resistance to localized plastic deformation (e.g., a small dent or a scratch).

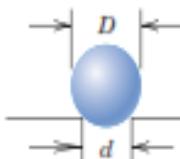
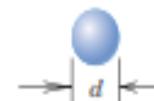
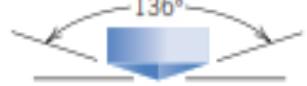
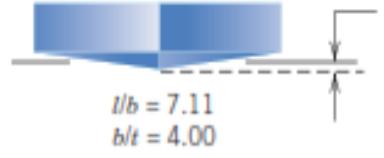
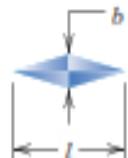
Early hardness tests were based on natural minerals with a scale constructed solely on the ability of one material to scratch another that was softer, termed the Mohs scale, which ranged from 1 on the soft end for talc to 10 for diamond.

Quantitative hardness techniques have been developed over the years in which a small indenter is forced into the surface of a material to be tested, under controlled conditions of load and rate of application. The depth or size of the resulting indentation is measured, which in turn is related to a hardness number. The softer the material, the larger and deeper is the indentation, and the lower the hardness index number.

Hardness tests are performed more frequently than any other mechanical test, because they are simple and inexpensive, relatively inexpensive, non-destructive and other mechanical properties often may be estimated from hardness data, such as tensile strength.



**Table 6.5 Hardness-Testing Techniques**

Test	Indenter	Shape of Indentation			Formula for Hardness Number <sup>a</sup>
		Side View	Top View	Load	
Brinell	10-mm sphere of steel or tungsten carbide			$P$	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			$P$	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid	 $t/b = 7.11$ $b/t = 4.00$		$P$	$HK = 14.2P/l^2$
Rockwell and Superficial Rockwell	Diamond cone: $\frac{1}{16}, \frac{1}{8}, \frac{1}{4}, \frac{1}{2}$ in. diameter steel spheres			$60 \text{ kg}$ $100 \text{ kg}$ $150 \text{ kg}$ $15 \text{ kg}$ $30 \text{ kg}$ $45 \text{ kg}$	Rockwell Superficial Rockwell
					

**Rockwell hardness test :** With this system, a hardness number is determined by the difference in depth of penetration resulting from the application of an initial minor load followed by a larger major load. Utilization of a minor load enhances test accuracy. On the basis of the magnitude of both major and minor loads.

The Rockwell tests constitute the most common method used to measure hardness because they are so simple to perform and require no special skills. Several different scales may be utilized from possible combinations of various indenters and different loads.

Indenters include spherical and hardened steel balls having diameters of 1/16, 1/8, 1/4 and 1/2 in. (1.588, 3.175, 6.350, and 12.70 mm), and a conical diamond (Brale) indenter, which is used for the hardest materials.

For Rockwell, the minor load is 10 kg, whereas major loads are 60, 100, and 150 kg for A, B and C scales respectively. Each scale is represented by a letter of the alphabet; several are listed with the corresponding indenter and load in Tables.



**Table 6.6a Rockwell Hardness Scales**

Scale Symbol	Indenter	Major Load (kg)
A	Diamond	60
B	$\frac{1}{16}$ -in. ball	100
C	Diamond	150
D	Diamond	100
E	$\frac{1}{8}$ -in. ball	100
F	$\frac{1}{16}$ -in. ball	60
G	$\frac{1}{16}$ -in. ball	150
H	$\frac{1}{8}$ -in. ball	60
K	$\frac{1}{8}$ -in. ball	150

In **Brinell tests**, as in Rockwell measurements, a hard, spherical indenter is forced into the surface of the metal to be tested. The diameter of the hardened steel (or tungsten carbide) indenter is 10.00 mm. Standard loads ranges between 500 and 3000 kg in 500-kg increments. during a test, the load is maintained constant for a specified time (between 10 and 30 s). Harder materials require greater applied loads. The Brinell hardness number, HB, is a function of both the magnitude of the load and the diameter of the resulting indentation. This diameter is measured with a special low-power microscope, utilizing a scale that is etched on the eyepiece. The measured diameter is then converted to the appropriate HB number using a chart.

Two other hardness-testing techniques are **Knoop** and **Vickers**. For each test a very small diamond indenter having pyramidal geometry is forced into the surface of the specimen. Applied loads are much smaller than for Rockwell and Brinell, ranging between 1 and 1000g. The resulting impression is observed under a microscope and measured. this measurement is then converted into a hardness number. The Knoop and Vickers hardness numbers are designated by HK and HV, respectively, and hardness scales for both techniques are approximately equivalent. Knoop and Vickers are referred to as micro-indentation testing methods on the basis of indenter size. Both are well suited for measuring the hardness of small, selected specimen regions. Knoop hardness is used for testing brittle materials such as ceramics.

**Viscoelastic** properties describe materials that exhibit both elastic and viscous behavior when deformed, meaning they can store energy like a spring and deform like a liquid. This time-dependent deformation is influenced by factors like temperature and strain rate.

Elasticity vs. Viscosity:

**Elastic:** Deforms instantaneously under stress and returns to its original shape when the stress is removed.

**Viscous:** Deforms gradually over time under stress and doesn't fully recover when the stress is removed.

**Viscoelastic deformation** is a type of material behaviour where the material exhibits both elastic (recoverable) and viscous (non-recoverable) characteristics under stress. This means the material deforms both instantaneously like a solid and also gradually deforms over time like a liquid.

Examples: Rubber bands, polymers, biological tissues such as Muscles, tendons, and other tissues.

Key Concepts of viscoelastic deformation:

**Strain-rate dependence:** The speed at which a viscoelastic material is stretched affects its behavior.

**Time-dependent deformation:** The deformation of a viscoelastic material occurs over time, unlike a purely elastic material.

**Hysteresis:** Viscoelastic materials may exhibit hysteresis in their stress-strain curves, meaning the stress-strain relationship is different during loading and unloading.

**Stress relaxation:** A viscoelastic material under constant strain will see the stress decrease over time.

**Creep:** A viscoelastic material under constant stress will see the strain increase over time.

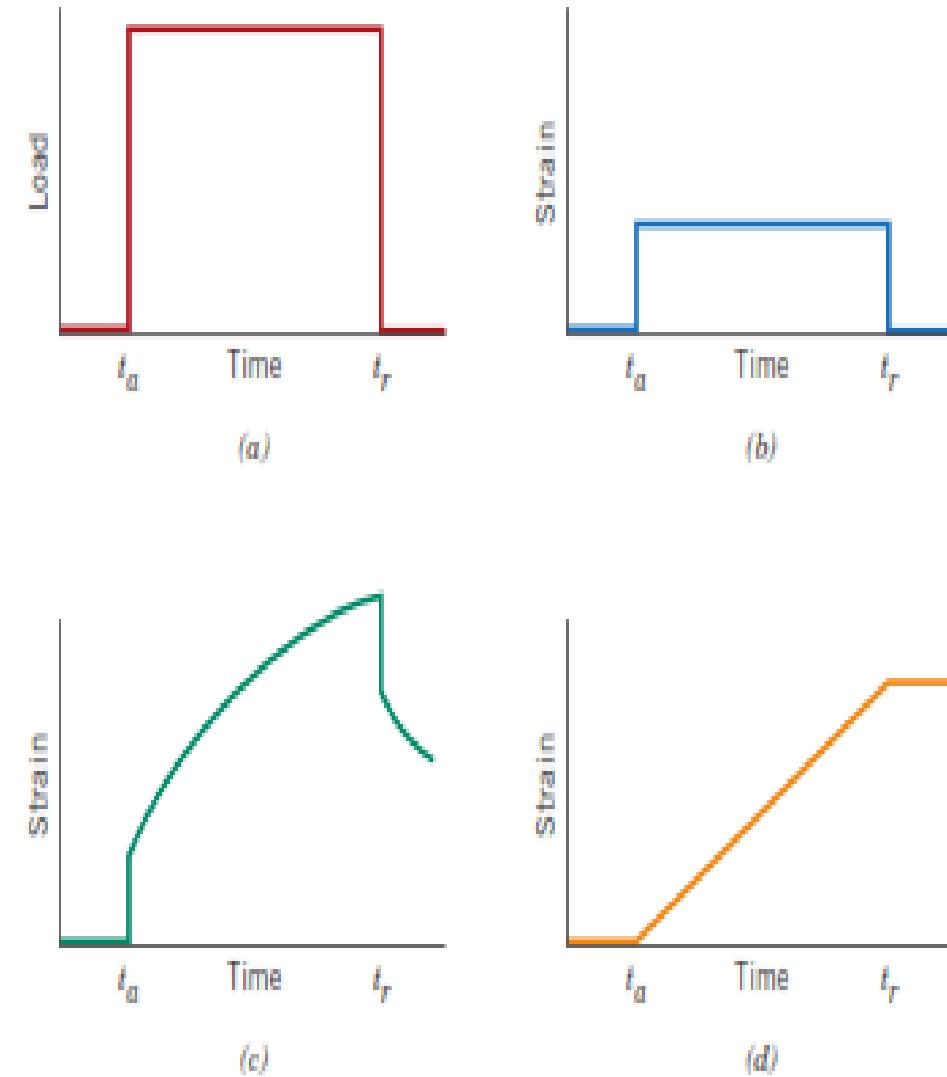
Elastic deformation is instantaneous, which means that total deformation (or strain) occurs the instant the stress is applied or released (i.e., the strain is independent of time). In addition, upon release of the external stress, the deformation is **totally recovered**—the specimen assumes its original dimensions. This behavior is represented in Figure 15.5b as *strain versus time for the instantaneous load–time curve*, shown in Figure 15.5a.

For the intermediate viscoelastic behavior, the imposition of a stress in the manner of Figure 15.5a results in an instantaneous elastic strain, which is followed by a **viscous, time-dependent strain**, a form of anelasticity, this behaviour is illustrated in Figure 15.5c.

By way of contrast, for totally viscous behavior, deformation or strain is not instantaneous; that is, in response to an applied stress, **deformation is delayed** or **dependent on time**. Also, this deformation is **not reversible** or completely recovered after the stress is released. This phenomenon is demonstrated in Figure 15.5d.

**Figure 15.5**

(a) Load versus time, where load is applied instantaneously at time  $t_a$  and released at  $t_r$ . For the load–time cycle in (a), the strain-versus-time responses are for totally elastic (b), viscoelastic (c), and viscous (d) behaviors.

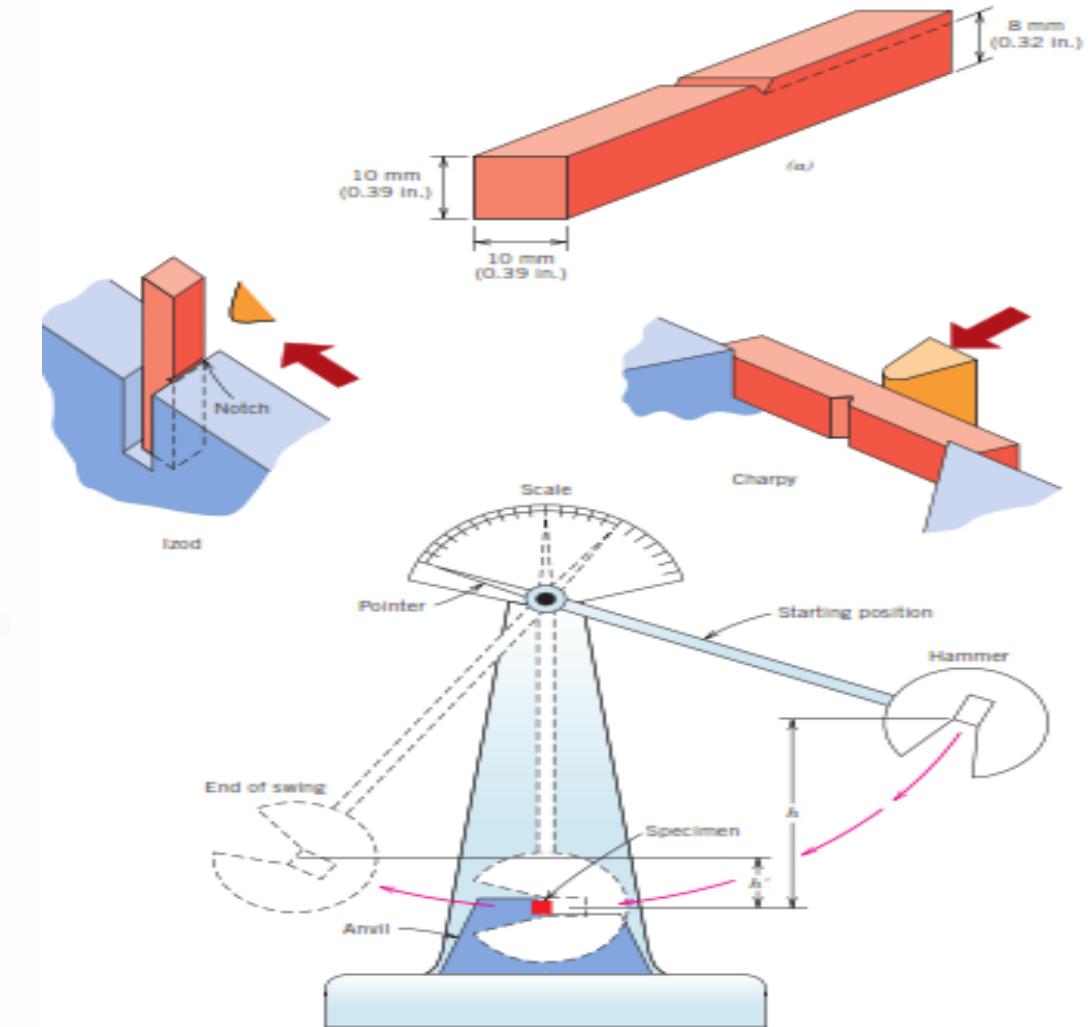


**Impact energy** refers to the energy absorbed by a material when subjected to a sudden, forceful impact. It's a measure of a material's toughness and its ability to resist fracture under high-velocity stresses.

The higher the impact energy, the more resistant a material is to breaking or fracturing under impulsive loads.

Figure shows *specimen used* for Charpy and Izod impact tests. A schematic drawing of an impact testing apparatus. The hammer is released from fixed height  $h$  and strikes the specimen. The energy expended in fracture is reflected in the difference between  $h$  and the swing height  $h'$ .

Specimen placements for both Charpy and Izod tests are also shown.

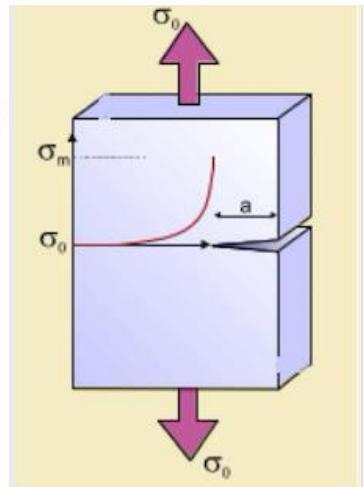


**Fracture toughness** is the measure of a material's resistance to brittle fracture when a crack is present. This property is a quantitative way of expressing a metal's resistance to crack propagation and standard values for a given material are generally available. It is directly related to the yield strength of the metal and the size of the crack. The term for fracture toughness is  $K_c$  and its value decreases with the thickness of the material according to the figure, until it reaches a more or less constant value, called  $K_{Ic}$ .

The fracture toughness  $K_{Ic}$  is expressed as  $K_{Ic} = Y \sigma \sqrt{(\pi.a)} \text{ Mpa } \sqrt{\text{m}}$ , where  $Y$  is a dimensionless parameter that depends on the geometry of the sample and the crack,  $\sigma$  is the applied stress and  $a$  is the length of the crack.

Brittle metals have low fracture toughness  $K_{Ic}$  and are susceptible to catastrophic defects while ductile metals have greater fracture toughness.

The fracture toughness  $K_{Ic}$  is a material-dependent property that depends on various factors. It decreases with increasing deformation rate and with decreasing temperature. An increase in the yield strength generally reduces fracture toughness. Normally, the fracture toughness increases with decreasing grain size of the metal.



In many engineering applications, components are required to withstand dynamic repeated or cyclic stresses, such as propeller shafts in aircraft, shafts, connecting rods in automobiles.

**Fatigue failures :** Under fluctuating / cyclic stresses, failure can occur at loads considerably lower than tensile or yield strengths of material under a static load. Such failures are termed as fatigue failures.

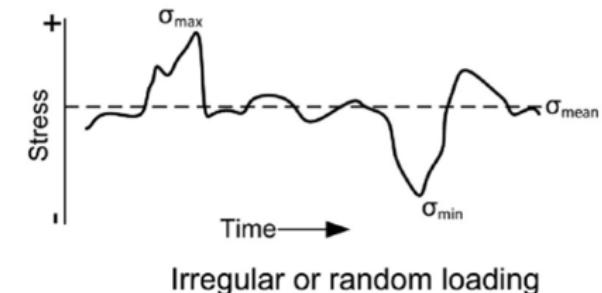
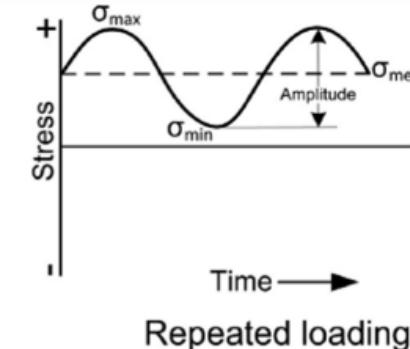
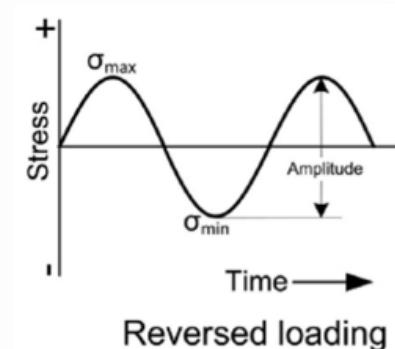
Fatigue failure is brittle-like (relatively little plastic deformation) - even in normally ductile materials. Thus sudden and catastrophic.

Applied stresses causing fatigue may be axial (tension or compression), flexural (bending) or torsional (twisting).

**Fatigue failure proceeds in three distinct stages:** crack initiation in the areas of stress concentration (near stress raisers), incremental crack propagation, final catastrophic failure.

## Types of fatigue loading

- Reversed stress cycle
- Repeated stress cycle
- Random stress cycle



Cyclic stresses are characterized by maximum, minimum and mean stress, the range of stress, the stress amplitude, and the stress ratio

Mean stress:

$$\sigma_m = (\sigma_{\max} + \sigma_{\min}) / 2$$

Range of stress:

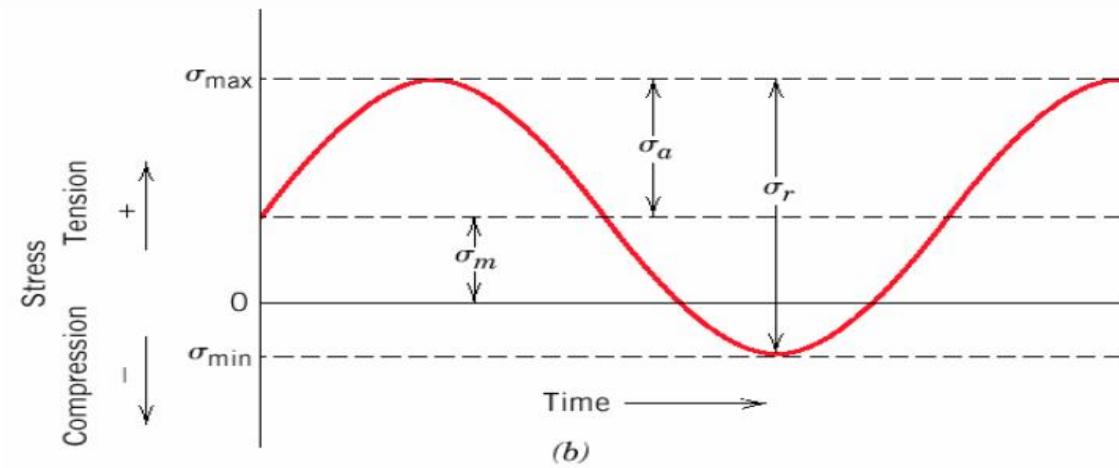
$$\sigma_r = (\sigma_{\max} - \sigma_{\min})$$

Stress amplitude:

$$\sigma_a = \sigma_r / 2 = (\sigma_{\max} - \sigma_{\min}) / 2$$

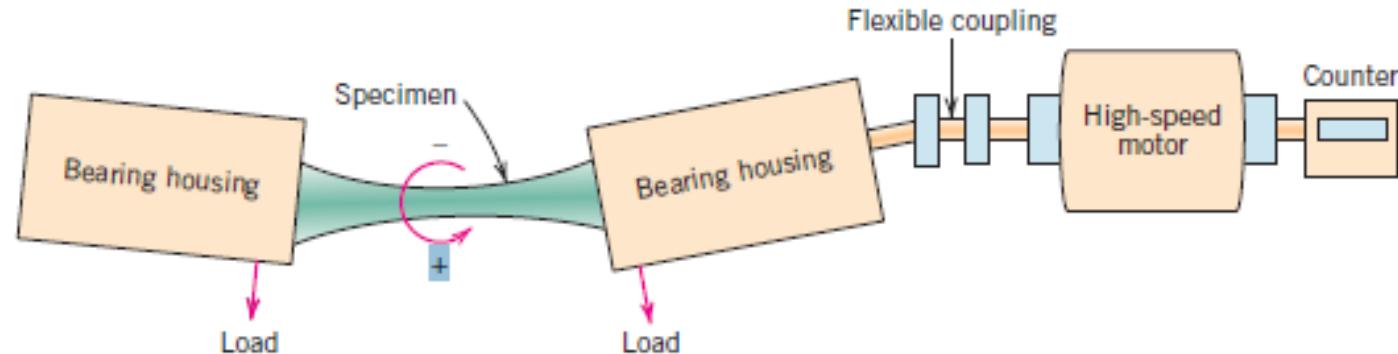
Stress ratio:

$$R = \sigma_{\min} / \sigma_{\max}$$



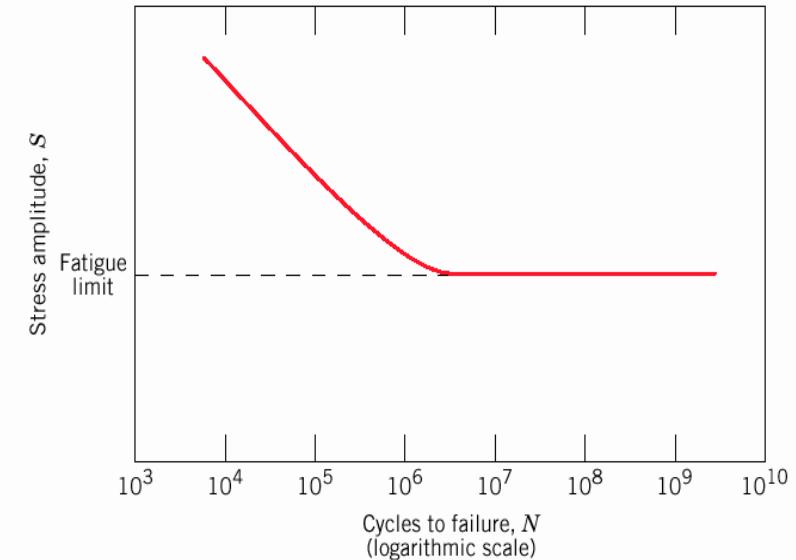
Remember the convention that tensile stresses are positive, compressive stresses are negative

Fatigue properties of a material are tested in **rotating-bending** testing apparatus shown in figure and result is commonly plotted as S (stress) vs. N (number of cycles to failure).

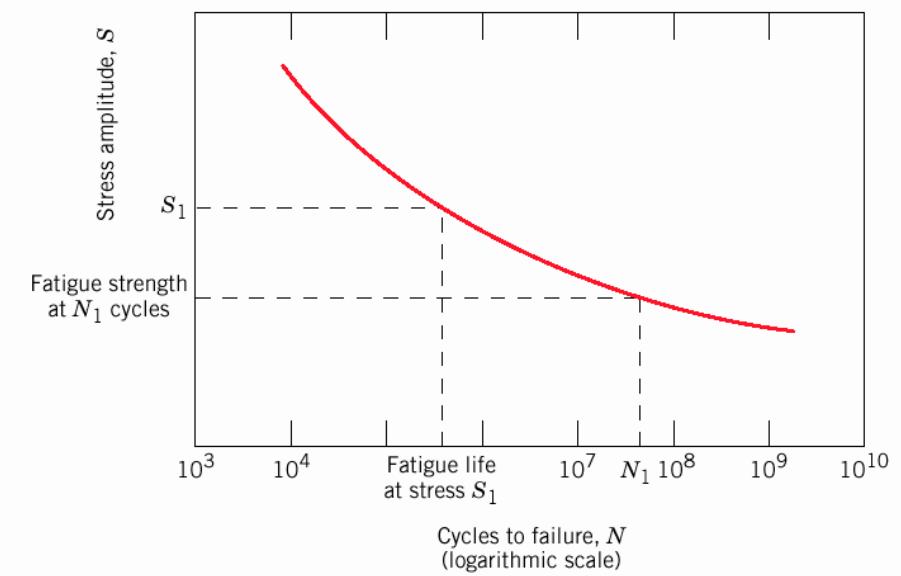


Schematic diagram of fatigue-testing apparatus for making rotating bending tests.

**Fatigue limit** (endurance limit) occurs for some materials (e.g. some Fe and Ti alloys). In this case, the S—N curve becomes horizontal at large N. The *fatigue limit is a maximum stress amplitude below which the material never fails, no matter how large the number of cycles is.*



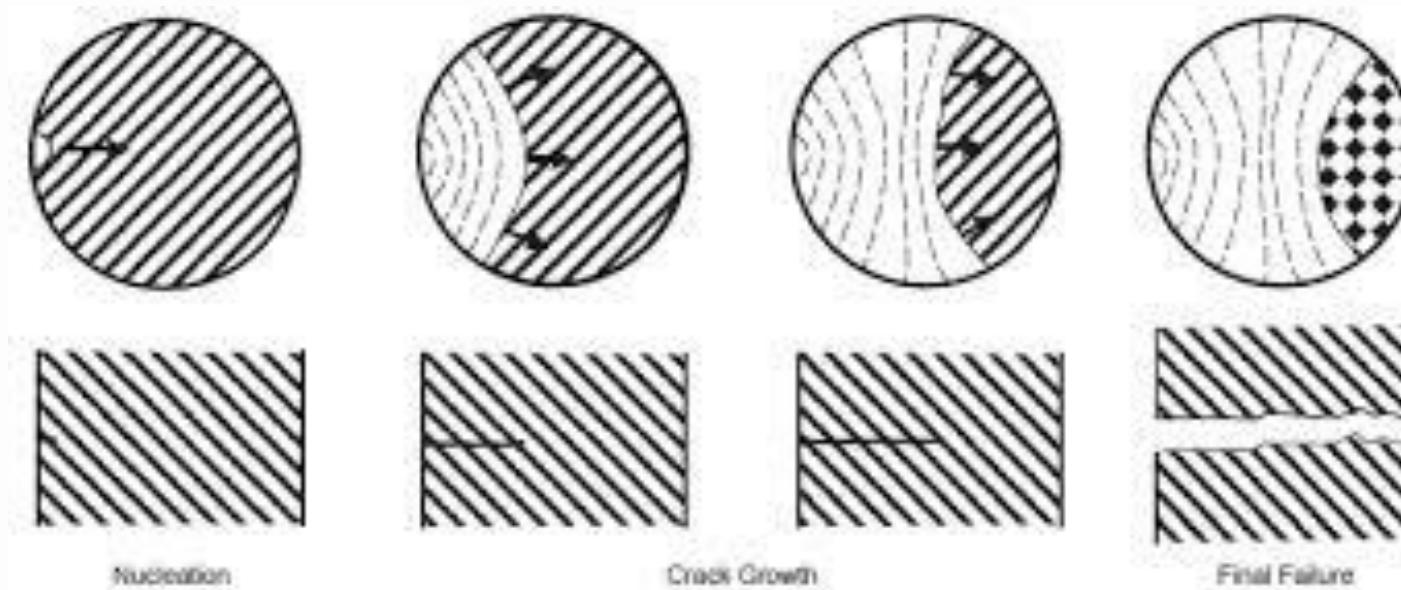
In most alloys,  $S$  decreases continuously with  $N$ . In this cases the fatigue properties are described by  
**Fatigue strength:** stress at which fracture occurs after a specified number of cycles (e.g.  $10^7$ )  
**Fatigue life:** Number of cycles to fail at a specified stress level



## Mechanism (stages) of fatigue failure:

1. Crack initiation
2. Crack propagation
3. Final catastrophic failure

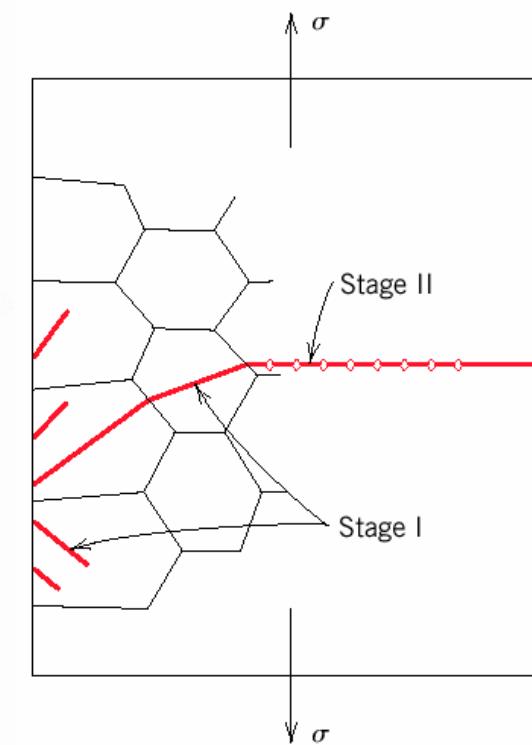
**Crack initiation:** At the early stages of the service life of the component, with the applied cyclic stress, a crack nucleate at some point of high stress concentration mostly on the surface. This may initiate at micro-cracks, scratches, indents, interior corners, dislocation slip steps, etc.).



**Crack propagation :** With increasing number of cycles, this crack propagates into the component at the direction approximately perpendicular to the tensile axis of loading. The crack grows in size and gradually propagates across the cross-section.

**Stage I :** Slow propagation of crack along crystal planes with high resolved shear stress involving just a few grains, and has flat fracture surface.

**Stage II :** Faster propagation of crack on planes of high tensile stress at the direction perpendicular to the applied stress known as stage II crack growth. Crack propagation rate is faster than stage I propagation. Crack grows by repetitive process of blunting and sharpening at the crack tip.



**Final catastrophic failure :** With the growth of crack, the cross-sectional area of the part becomes so small that at some stage it can no longer sustain the applied load. For the same applied load, the stress keeps on increasing with continuously reducing cross-sectional area, and finally leads to a fracture. A fracture surface due to fatigue failure illustrates two types of regions. The first region is smooth area that is produced by the rubbing action of two surfaces, followed by a rough area indicates the sudden failure.

## Factors affecting fatigue life – Enhancing fatigue life

### 1. Material Properties

**Material Strength and Toughness:** Stronger and tougher materials, which can absorb more energy before fracturing, also tend to have better fatigue resistance.

**Grain Size:** Smaller grain sizes can increase fatigue strength.

**Inclusions:** Defects or inclusions in the material can act as stress concentrators, reducing fatigue life.

**Residual Stress:** Residual stresses (stresses remaining in a material after manufacturing or processing) can significantly impact fatigue, with tensile residual stresses reducing fatigue life and compressive stresses enhancing it.

**Microstructure:** The internal structure of the material, including things like grain boundaries and phase transformations, can influence fatigue behavior.

### 2. Load Characteristics

**Stress Amplitude:** The magnitude of the stress fluctuations during cyclic loading is a primary factor affecting fatigue life. Higher stress amplitudes shorten fatigue life.

**Stress Ratio (R-ratio):** The ratio of the minimum stress to the maximum stress during a cycle influences fatigue life. A higher R-ratio (meaning more positive mean stress) can reduce fatigue life.

**Frequency:** The speed at which the load cycles can affect fatigue life.

### 3. Environmental Conditions

**Temperature:** High temperatures can reduce the fatigue strength of materials, while low temperatures can increase brittleness, affecting fatigue life.

**Corrosion:** Corrosive environments can weaken materials at a microscopic level, leading to fatigue crack initiation and propagation.

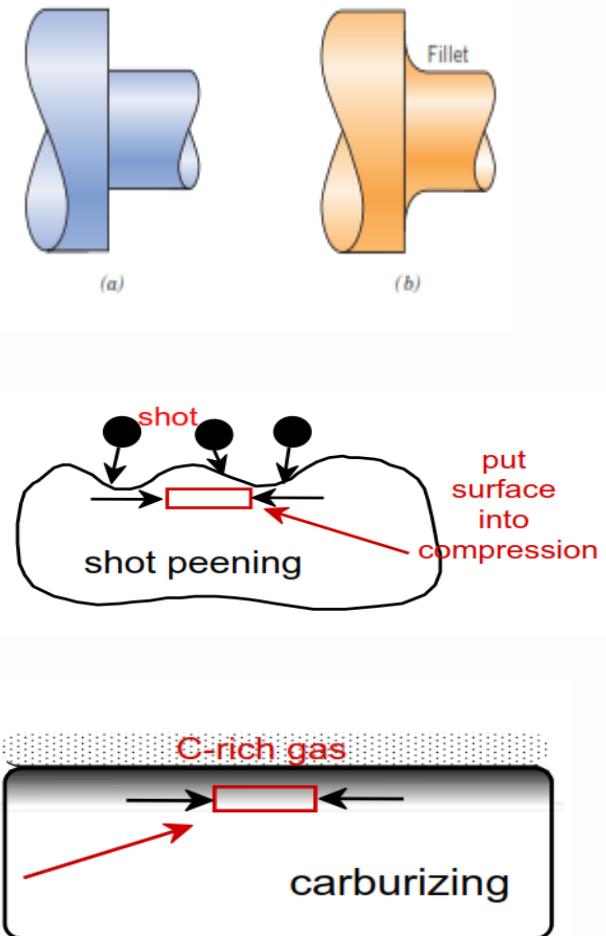
**Humidity:** Fluctuations in humidity can affect materials like polymers and composites, altering their mechanical properties and potentially reducing fatigue life.

### 4. Manufacturing and Design

**Stress Concentration:** Geometrical features like sharp corners, holes, and notches can concentrate stress, creating areas where fatigue cracks are more likely to initiate.

**Surface Condition:** Surface defects like scratches, cracks, or roughness can act as stress concentrators and reduce fatigue life.

**Surface Treatments:** Surface treatments like shot peening, case hardening, or coating can enhance fatigue resistance.



*The End*