

# Materials

## *Definitions*

**Brittle** – Breaks suddenly and catastrophically with rough edges;

- Little extension before fracture.
- Once started, cracks propagate easily.
- Brittle materials are very stiff.
- Bricks and glass are brittle.

**Tough** – The opposite of brittle;

- The material resists crack propagation and so distorts rather than breaks;
- It can withstand shock and impact.
- Nylon, Kevlar, rope, bones, tendons and most textiles are tough.

**Durable** – Can withstand repeated loading and unloading.

**Strong** – The material needs a large stress to distort it;

- Steel, titanium alloys, rubber, glass, wood (along the grain) and cotton are strong.
- The metals are about 10 times stronger than the non-metals
- The more boundaries there are, the stronger the material is.

**Strength** – How much force can be applied without breaking the material.

**Stiffness** – A measure of the difficulty of changing the shape of an object.

**Elastic** – The material will return to its original length (or shape) when any load is removed;

- Rubber, steel, glass and wood are usefully elastic – they withstand everyday forces without permanent distortion.

**Elasticity** – The property which allows a material to regain shape after distortion.

**Elastic Limit** – The maximum amount a material can be stretched and still regain its original shape.

**Plastic** – The material distorts easily with quite small stresses but does not fracture;

- This happens after a material has reached it's elastic limit, i.e. It has no elasticity.
- Plasticine and wet clay are typical plastic materials;
- Metals and ice show plastic behaviour if stresses act for a long time (metals creep, glaciers flow)

**Hard** – Hard materials are not easily cut or scratched;

- Diamond is hard, graphite is soft (hardness is measured on a scale from 1 – 10 using Mohs scale)

**Hardness** – The relative resistance of a material to scratching, denting or bending.

**Soft** – The opposite of hard

**Creep** – Occurs when a material, acted on by constant forces, changes its shape even though the forces remain constant.

- Rather than failing suddenly with a fracture, the material strains over a long period of time until it finally fails.

**Malleable** – Material changes shape but does not crack when subjected to sudden large forces (e.g. being hit with a hammer);

- Being capable of deformation, especially by hammering, bending or rolling;
- Many metals (e.g. Copper) are malleable

**Ductile** – Material changes shape rather than cracking when subjected to a large but steadily applied force;

- Being capable of sustaining large plastic deformations without fracture.
- Cracks at the surface do not become larger – the atoms slide over one another to prevent the crack tip from growing.
- Describes the behaviour of many metals which can be drawn out into wires when forced through a small hole.

**Yield** – A condition in materials under tensile stress where it becomes plastic, deformation is large and the material will ultimately break.

**Shear** – Is caused when a material is acted on by two equal and opposite forces, not in the same straight line.

- For a material under stress due to shear forces, the shear stress applied to it is defined as the force per unit area acting tangentially on the area resisting shear.

**Bending** – May cause a material to fracture.

- Bending a metre rule too much and it will fracture on the outer side of the bend.
- This is because the outer side is in tension because it is stretched whereas the inner side of the bend is in compression because it is squeezed.
- The rule snaps because it cannot withstand the tension on the outer side.

### *Ceramics and Glass*

Ceramics and glass are very brittle because the atoms are joined together in strong bonds which are **directional**. When a crack builds up at the surface of a material, stress builds up at the tip of the crack. In a metal, the planes of atoms slip past each other to prevent the crack progressing into the metal. This cannot happen in ceramics or glass because the atoms cannot slip past each other as they are not linked together in planes. Hence a crack in a ceramic propagates easily, causing **brittle fracture**.

Glass can be classified as a ceramic because it is strong and brittle for the same reasons: the bonds are directional so the atoms cannot slip past each other as in a metal. Covalent bonds join the atoms together in a giant, rigid structure. Glass molecules form a disordered structure. Glass is an example of an **amorphous** structure because there is no pattern in the arrangement of its atoms. Glass is transparent whereas most ceramics are not. This is because the boundaries in a ceramic scatter light. There are no boundaries in glass because it is amorphous.

### *Rubber*

In a piece of rubber, the molecules are tangled up with one another, until the rubber is stretched and then they straighten out. The molecules are in disorder when unstretched but when stretched, it does show a *crystal-like* x-ray diffraction pattern. This is because they are parallel to one another when stretched. Stretched rubber can be termed crystalline because there is some order. When stretched

rubber is released, it regains its original shape because the molecules curl up and tangle together again. The stretchiness of rubber occurs because its molecules are tangled together in the unstretched state. Its elasticity occurs because the molecules curl up when released.

### *Hooke's Law*

The extension or compression of a spring is proportional to the load applied provided that the spring does not exceed its elastic limit.

$$F = kx$$

Where  $F$  is the force applied (N),  $k$  is the elastic constant ( $\text{Nm}^{-1}$ ) of the material, and  $x$  is the extension (m).

### *Strain*

Strain is defined as the extension per unit length:

$$\text{Strain} = \text{extension (m)} / \text{original length (m)}$$

Because it is metres / metres, strain has **no units**.

### *(Tensile) Stress*

Stress is defined as the tension (force) per unit area applied at right angles to that area.

$$\text{Stress (Nm}^{-2}\text{)} = \text{Force (N)} / \text{Area (m}^2\text{)}$$

Note that a Pascal (Pa) is the same as a  $\text{Nm}^{-2}$ .

### *Young's Modulus*

When stress is applied to a material, strain is produced. The strain is proportional to the stress, provided the stress does not exceed a limit known as the **limit of proportionality**. Within this limit, the value of stress/strain is a constant for that material, known as the Young Modulus for the material.

$$\text{Young's Modulus} = \text{Stress/Strain}$$

As strain has no units, the Young's modulus is also measured in  $\text{Nm}^{-2}$ . The Young's modulus of a material is a measure of how **stiff** it is.

### *Factors Affecting Resistance*

- **Resistivity** - is an intrinsic property of a particular material. It depends on many factors e.g. density, structure, position of shells etc.
- **Cross-Sectional Area** - the smaller the cross-sectional area of a material, the less room there is for electrons to flow. They are therefore more likely to collide with each other and other particles.
- **Length** - the longer the piece of material you have, the more total particles there are which the electrons have to pass. There is therefore a higher chance of collision.
- **Temperature** - the higher the temperature, the more energy particles have, hence they vibrate

more. The more they vibrate, the harder it is to pass them without colliding.

At a constant temperature:

- Resistance is proportional to length
- Resistance is proportional to 1 / cross-sectional area
- Resistance is proportional to Resistivity

From these facts, this formula can be derived:

$$\text{Resistance } (\Omega) = (\text{Resistivity } (\Omega \cdot \text{m}) \times \text{Length } (\text{m})) / \text{Cross-sectional Area } (\text{m}^2)$$

$$R = \rho l / A$$

$$\rho = 1 / \sigma$$

Where  $\rho$  is the resistivity (ohm-metres), and  $\sigma$  is the conductivity (siemens.m<sup>-1</sup>).

$$G = \sigma A / l$$

Note that if we want to know the cross sectional area of, say, a wire (very small area) we can use a **micrometer screw gauge**.

### *Conduction through solids*

A material conducts electricity if it has free electrons. Non-metals tend to have covalent bonds, metals have metallic bonds.

In metals, each atom in a **lattice** supplies some free electrons which are mobile. The electrons move quickly in all directions.

When a battery is connected, the electrons begin to drift in one direction (towards the positive node). But because they collide with other electrons, there are electrons flowing in all directions. They are said to have a **drift velocity** (see below).

An electron becomes excited and jumps to a higher orbital. It is then unstable and releases EM radiation to become stable again. The ionisation energy is the energy needed remove an electron from an atom. In metals, the electrons are in the conductance band (the outer shells) and hence they can flow easily. It is harder for insulators to conduct electricity because their electrons are in their valence bands (nearer the nucleus).

### *Drift Velocity*

Drift velocity is the average velocity of the electrons moving when a current is flowing (about  $1 \times 10^5 \text{ ms}^{-1}$  in wires). The electrons want to move in a straight line but will collide with atoms and other electrons. The result is that some electrons are moving in every direction. The average velocity will be from negative to positive and this is the drift velocity.

### *Conductors and Insulators*

A good **conductor** has lots of free electrons which move around in a certain direction when a p.d. is applied.

- When it is cold, the nuclei don't move much – resistance decreases.
- When it is hot, the nuclei move around a lot – resistance increases.
- When it is very cold (-200°C), we get superconductors (e.g. Cu, Al etc.) - no resistance, large current (nuclei are stationary making electrons flow very easily).
  - Used for particle accelerators, levitating trains, medical equipment etc.

An **insulator** has electrons which are tightly held around the nuclei – the electrons are in the valence band.

A **semiconductor** (Si, Ge etc.) has a few free electrons (1 in  $10^{12}$ )

- When a semiconductor is hot, a **greater** current will flow because there are more free electrons (which overcome the nuclei moving around more). This is because the electrons become excited into the conduction band.

### *Mechanism of current flow in semiconductors*

- A free electron moves towards the positive charge and leaves a hole.
- A second electron breaks free, fills in the old hole, and makes a new hole.
- A third electron breaks free, fills in the hole and makes a new hole. The electrons move towards the positive end, and the holes move towards the negative. Hence we can think of holes as a positive, imaginary, particle.
- In order to gain more electrons, we **dope** silicon with, usually, phosphorus (n-type material), and we dope germanium with arsenic (n-type material).
  - because phosphorus has an extra electron in its outer shell, compared to Si, it gives more free electrons. There are now more negative charges, and hence we call it n-type doping.
- In order to gain more holes, we dope Si with aluminium, and Ge with gallium.
  - because Al has one less electron compared to Si, doping it with Si makes more holes. Because the holes are positive, we call it p-type doping.

In all electronic devices, there are integrated circuits which contain n- and p-type materials. These can either be used as switches or amplifiers. A 2GHz processor is the number of switches switching on an off per second. Originally, there was something called a vacuum tube, which was a very basic diode, or switch. Valves started to be produced, and were used in everything electrical.

### *Refraction*

When waves cross a boundary between two materials there is a change of speed, called **refraction**. If the direction of the wave travel is at any other angle other than along the normal line, this change in speed causes a change in direction. Note that there is always some reflection at a boundary where refraction takes place.

As some parts of the light will hit the glass first, not only does the angle change, but the wave also becomes compressed, giving a smaller wavelength and higher frequency. The change in speed is described by the **refractive index**.

$$n = \text{speed of light in vacuum} / \text{speed of light in material}$$

Where  $n$  is the refractive index, and the speed of light in a vacuum is  $3 \times 10^8 \text{ms}^{-1}$ .

$$n = \sin i / \sin r$$

This is called **Snell's Law**, where  $i$  is the angle of incidence, and  $r$  is the angle of refraction.

As the refractive index is a ratio, it does not have any units. The refractive index is the factor by which the speed of light is reduced when it passes from a vacuum into the material. This is sometimes called the **absolute refractive index** to distinguish it from the **relative refractive index** between two materials:

$$\begin{aligned} n &= \text{speed of light in material 1} / \text{speed of light in material 2} \\ &= n_1 / n_2 \end{aligned}$$

Where  $n_1$  is the refractive index of material 1, and  $n_2$  is the refractive index of material 2.

The greater the change in speed when light is refracted, the greater the change in direction. Hence the greater the refractive index, the greater the change in direction.

When light speeds up as it crosses a boundary, the change in direction is away from the normal line. For some angle of incidence, called the **critical angle**, the angle of refraction is  $90^\circ$ .

- At angles of incidence less than the critical angle, both reflection and refraction take place.
- At the critical angle, the angle of refraction is  $90^\circ$ .
- At angles of incidence greater than the critical angle, the light is totally internally reflected.

$$n = 1 / \sin C$$

Where  $C$  is the critical angle.

$$n = \text{real depth} / \text{apparent depth}$$