ENGINEERING COUNCIL

CERTIFICATE LEVEL

ENGINEERING MATERIALS C102

TUTORIAL 5 – NON-MECHANICAL PROPERTIES OF MATERIALS

OUTCOMES
On successful completion of the unit the candidate will be able to:

1. Recognise the structures of metals, polymers and ceramic materials.
2. Assess the mechanical and physical properties of engineering materials
3. Understand the relationships between the structure of a material and its properties.
4. Select materials for specific engineering applications.

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1. ELECTRICAL PROPERTIES

CONDUCTIVITY

This property governs how well the material conducts electricity. The best material is silver but this is too expensive so for general use copper is the best compromise. Materials with bad conductivity may be used as insulators. These are various polymers and ceramics. The formula for calculating the resistance of a wire is as follows.
$R = \rho A/L$ where ρ is the resistivity, L the length and A is the cross sectional area.

RESISTIVITY

The resistance of a conductor increases with length L and decreases with cross sectional area A so we may say R is directly proportional to L and inversely proportional to A.

R = Constant x L/A
The constant is the resistivity of the material ρ hence $R = \rho L/A$ Ohms

SELF ASSESSMENT EXERCISE No.1

1. Calculate the resistance of a copper wire 5 m long and 0.3 mm diameter. The resistivity is 1.7×10^{-8} Ohm metre. (Answer 1.202 Ω)

2. Calculate the resistance of a nichrome wire 2 m long and 0.2 mm diameter given $\rho = 108 \times 10^{-8}$
(Answer 68.75 Ω)

RELATIVE PERMEABILITY

This is a property that governs the magnetic strength of a material. The symbol is μ_r. This is a property that is difficult to give as a constant in tables and you need to understand magnetisation in depth to follow how to use this property. The main equation that this property occurs is $B/H = \mu_o\mu_r$
B is the flux density in Tesla, H is the magnetising force and μ_o is the absolute permeability with a value of 12.566×10^{-7}

RELATIVE PERMITTIVITY

This is a property that governs the electro-static charge stored on an electric capacitor. The symbol is ε_r. The main equation that this is found in is $\mathbf{C = \varepsilon_o\varepsilon_r A/d}$
C is the capacitance in Farads and A the area of the capacitor plates and d the distance between them. ε_o is the absolute permittivity with a value of $\varepsilon_o = 8.85 \times 10^{-12}$
Here is a table of some common figures.

MATERIAL	ε_r
Free Space	1.000
Air	1.006
Paper	2 approx.
Glass	7 approx.
Mica	4 approx.
Ceramic	6 approx.
Plastics	various

TEMPERATURE COEFFICIENT OF RESISTANCE

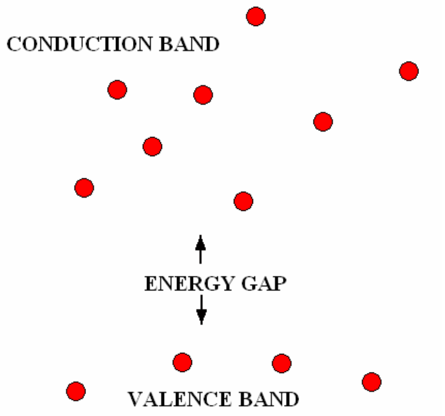
The resistance of most conductors increases with temperature. This is a problem for items like electrical strain gauges where the changes in resistance must be due to the change in the dimensions only. (There are special materials like semiconductors where the resistance goes down with increased temperature covered in the next section). The amount by which the resistance changes per degree per ohm of the original resistance is called the temperature coefficient of resistance and is denoted α. The units are Ohms per Ohm per degree.

Let the resistance of a conductor be R_o at 0^oC.
Let the resistance be R_1 at θ_1 ^oC. The change in resistance = $\alpha\theta_1 R_o$
The new resistance is $R_1 = R_o + \alpha\theta_1 R_o$
Let the resistance be R_2 at θ_2 ^oC. The change in resistance = $\alpha\theta_2 R_o$
The new resistance is $R_2 = R_o + \alpha\theta_2 R_o$
If the temperature changes from θ_1 to θ_2 the resistance changes by
$\Delta R = R_2 - R_1 = (R_o + \alpha\theta_2 R_o) - (R_o + \alpha\theta_1 R_o)$ $\quad$ $\mathbf{\Delta R = R_o \alpha\Delta\theta}$

SELF ASSESSMENT EXERCISE No. 2

1. A resistor has a nominal resistance of 120 Ω at 0 ^oC. Calculate the resistance at 20^oC. Calculate the change in resistance when the temperature drops by 5 degrees. $\alpha = 6 \times 10^{-3}\ \Omega/\Omega\ ^oC$
   (Answers 134.4 Ω and - 3.6Ω)

SEMICONDUCTOR THEORY



There are a group of natural materials that are neither good conductors nor good insulators. These are called semi conductors such as Silicon and Germanium. These are used to make a range of devices that are used in modern electronic circuits. To understand the electrical properties of these materials we need to go back to the atomic level. Electrons orbit in shells of fixed radius representing different fixed energy bands. The outer band of electrons on an atom is called the VALENCE band. The cloud of free electrons surrounding the molecules is called the CONDUCTION band. In a good conductor the electrons will leave the valence band and join the conduction band very easily and these electrons are free to form a current when a voltage is applied. The opposite is true of a good insulator.

The band theory supposes that a fixed amount of energy is required to make an electron jump from the valence shell into the conduction band. This is called the energy gap. The energy gap is large for the molecules of a good insulator but for a good conductor it is zero.

The resistance and resistivity of most conductors like copper increases with temperature but in the case of semi conductors like silicon the resistance goes down. Semi conductors are widely used to make temperature sensors (e.g. Thermistors) and a simple experiment with one of these will show that the resistance goes down quite dramatically when plunged into hot water.

Natural semi conductors are called **INTRINSIC.** When they are modified by a manufacturing process to give them enhanced properties, they are then called **EXTRINSIC.**

The Silicon atom has 14 electrons, two in the inner shell, eight in the second shell, and only four in the valence shell making it incomplete. This affects the way the atoms bond together in a crystalline form. There are no free electron and no conduction band. In such materials, the energy required to make an electron jump the energy gap can come from heat. This means that at temperature above absolute zero, say room temperature, some electron will jump the energy gap to become free electrons. The number of electrons in the conduction band rises with temperature and explains the negative thermal coefficient of resistance.

When an electron makes this jump to the conduction band the parent atom becomes deficient and most text refers to this as a **HOLE** because it can be filled by another electron. When current flows in a semi conductor, the electrons can migrate from atom to atom so these HOLES appear to migrate in the opposite direction to the electron and this constitutes a current as well. These might be though of as equivalent to a positively charged particle moving in the opposite direction to the electron.

Extrinsic semi conductors are produced by doping them to enhance their conductivity. The conductivity of semiconductors like Silicon can be increased by adding small, controlled amounts of "impurities" that have roughly the same atomic size, but more or fewer valence electrons than the semimetal. This process is known as **doping**.

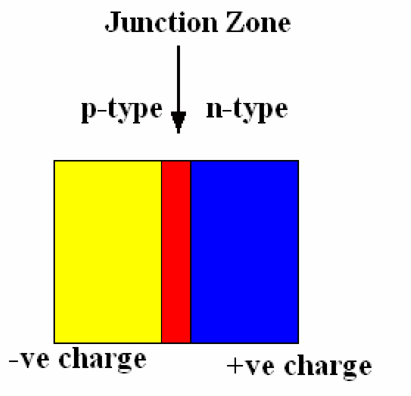
An impurity with fewer valence electrons such as boron, aluminium or indium takes up space in the solid structure, but contributes fewer electrons to the valence band, thus generating an electron deficit and making the atoms more positively charged. This type of doping creates a hole in the valence band making it possible for the electrons in the valence band to move atom to another within this band and so increases the conductivity. Such dopes semiconductors are known as ***p-type*** because the atoms are more positively charged.

Alternately, an impurity with more valence electrons such as phosphorus, antimony or arsenic contributes extra electrons to the band. Since the valence band is already filled by the semimetal, the extra electrons must go into the conduction band. This also improves the conductivity. Such dopes semiconductors are known as ***n-type*** because the enrichment of electrons makes it more negatively charged.

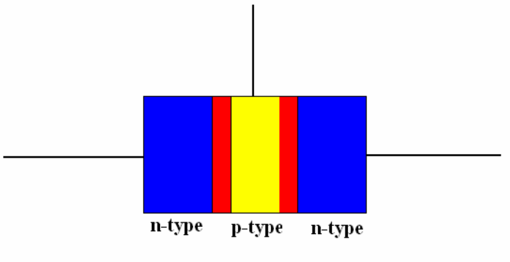
SEMICONDUCTOR JUNCTION

Consider what happens when a p-type and n-type material are brought together to form a junction. On their own there is an electron surplus in the n-type material and hole surplus in the p-type. When the two pieces are brought into contact, electrons from the n-type diffuse into the p-type creating a junction zone with few charge carriers. This balancing out of electrons only occurs in the junction zone.

If a voltage is applied across the junction, electrons can easily move from the p-type to the n-type but cannot flow in the reverse direction. The junction is a **DIODE**

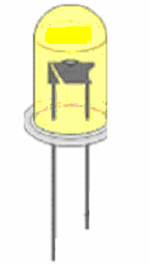


If we use two junctions we have a **TRANSISTOR**. You can get more on transistor theory at http://www.tpub.com/neets/book7/25a.htm



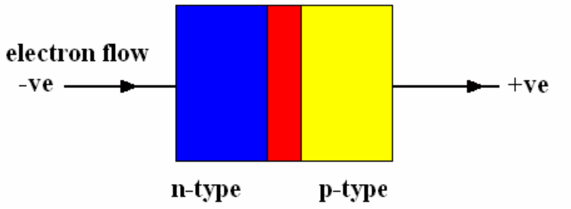
You can have n-p-n or p-n-p transistors. By injecting or removing electrons at the junction, the junction zones can be made to conduct and so pass a much larger current and producing a gain.

LIGHT EMITTING DIODES (LEDs)



These are diodes that give out light when a voltage is applied to them. They are made with semiconductor materials that have been specially enhanced. When a voltage is applied to a *p-n* junction, external electrons from the source flow to the diode and change the arrangement of electrons in the diode.

Recall that the *p*-type semiconductor has extra space for electrons in its valence band, and no electrons in its conduction band, while the *n*-type semiconductor has a full valence band and extra electrons in its conduction band.



If the circuit is connected as shown, electrons flow into the *n*-type side and occupy the conduction band. As electrons continue to come into the conduction band, they will be pushed to the *p*-type side. The electrons go into the empty conduction band of the *p*-type side. Since this is a higher energy band and the condition is not stable, they then jump to the valence band making the atoms more stable and in so doing must give up energy as light and the colour depends on the size of the energy gap. Red is produced by small gaps and yellow by large gaps.

SELF ASSESSMENT EXERCISE No. 3

From the 2004 Exam paper

Explain with reference to band structure and energy levels, the difference between intrinsic and extrinsic semiconductors.

Temperature has an effect on electrical conductivity. Describe and explain how conductivity will vary with temperature for the following materials.

Pure Copper
Pure Silicon
Silicon lightly doped with phosphorus.

Describe how semiconductor materials can be used to produce a light-emitting diode (LED). Describe the operation of the LED. What controls the colour of the light emitted during operation?

2. THERMAL PROPERTIES

MELTING POINT

This is the temperature at which the material melts and it is denoted Tm (K) or θm ^{o}C. Here is a table of the melting points of metals.

Elements	Symbol	θ m ^{o}C
Aluminum	Al	659
Brass (85 Cu 15 Zn)	Cu+Zn	900-940
Bronze (90 Cu 10 Sn)	Cu+Sn	850-1000
Cast Iron	C+Si+Mn+Fe	1260
Carbon	C	3600
Chromium	Cr	1615
Copper	Cu	1083
Gold	Au	1063
Hydrogen	H	-259
Inconel	Ni+Cr+Fe	1393
Iron	Fe	1530
Lead	Pb	327
Magnesium	Mg	670

Elements	Symbol	θ m ^{o}C
Manganese	Mn	1260
Monel	Ni+Cu+Si	1301
Nickel	Ni	1452
Phosphorous	P	44
Silicon	Si	1420
Silver	Ag	961
Stainless Steel	Cr+Ni+Mn+C	1363
Steel-High Carbon	Cr+Ni+Mn+C	1353
Medium Carbon	Cr+Ni+Mn+C	1427
Low Carbon	Cr+Ni+Mn+C	1464
Tin	Sn	232
Titanium	Ti	1795
Tungsten	W	3000
Zinc	Zn	419

LATENT HEAT OF FUSION

This is the energy required to melt 1 kg of material.

THERMAL CONDUCTIVITY

This is a property that governs how well a material conducts heat. The formula for the heat flow rate through a wall of area A is given by the following formula.

$$\Phi = k\ A\ \Delta\theta/t$$

Φ is the heat flow rate in Watts.
k is the thermal conductivity in W/m K
t is the thickness of the wall.
Δθ is the temperature difference between the two sides of the wall.

THERMAL EXPANSION

When solids and liquids are heated, the molecules vibrate more and take up more space so the material expands. Consider first the expansion in one direction.

If a bar of material of length L_o has its temperature increased by $\Delta\theta$ degrees, the increase of length is ΔL.

This is directly proportional to the original length L and to the temperature change $\Delta\theta$. It follows that :-

$$\Delta L = \text{constant x } L_o \, \Delta\theta$$

The constant of proportionality is called the coefficient of linear expansion (α).

$$\Delta L = \alpha \, L_o \, \Delta\theta$$

WORKED EXAMPLE No. 1

A thin steel band 850 mm diameter must be expanded to fit around a disc 851 mm diameter. Calculate the temperature change needed. The coefficient of linear expansion is 15×10^{-6} per ^{o}C

SOLUTION

Initial circumference of ring = $\pi D = \pi \times 850 = 2670.35$ mm
Required circumference = $\pi \times 851 = 2673.50$ mm
$\Delta L = 2673.50 - 2670.35 = 3.15$ mm
$\Delta L = \alpha \, L \, \Delta\theta$
$3.15 = 15 \times 10^{-6} \times 2670.35 \times \Delta\theta$
$\Delta\theta = 3.15/(15 \times 10^{-6} \times 2670.35) = 78.6$ Kelvin

SUPERFICIAL EXPANSION

This is about the change in area of a flat shape. Consider a flat plate of metal with area A_o. The change in area is ΔA and this is directly proportional to the temperature change so:-

$$\Delta A = \text{constant x } A_o \, \Delta\theta$$

The constant is the coefficient of superficial expansion β

$$\Delta A = \beta \, A_o \, \Delta\theta$$

Note $\beta = 2\alpha$

WORKED EXAMPLE No. 2

A steel sheet has an area of 500 cm^2 at 20^{o}C. Calculate the area when it is heated to 300 ^{o}C. The coefficient of superficial expansion is 30×10^{-6} per ^{o}C

SOLUTION

$\Delta A = \beta \, L \, \Delta\theta = 30 \times 10^{-6} \times 500 \times (300 - 20) = 4.2 \text{ cm}^3$
The new area is 504.2 cm^2

CUBICAL EXPANSION

Since a material expands in all direction the volume changes. The change in volume is ΔV.

This is directly proportional to the original volume V_o and to the temperature change $\Delta\theta$. It follows that :-

$$\Delta V = \text{constant x } V_o\,\Delta\theta$$

The constant of proportionality is called the coefficient of cubical expansion expansion (γ).

$$\Delta L = \gamma\, L\, \Delta\theta$$

Note that $\gamma = 2\,\alpha$

WORKED EXAMPLE No. 3

Calculate the change in volume of 1 m^3 of water when it is heated from 10 ^oC to 80 ^oC. The coefficient of cubical expansion is 210 x 10^{-6} per ^oC

SOLUTION

$\Delta V = 210 \text{ x } 10^{-6} \text{ x } 1 \text{ x } (80 - 10) = 14.7 \text{ x } 10^{-3}\ m^3$ or 14.7 dm^3 or 14.7 litre

SELF ASSESSMENT EXERCISE No.4

1. A brass bar is 600 mm long and 100 mm diameter. It is heated from 20 ^oC to 95^oC. Calculate the change in length. α is 18 x 10^{-6} per ^oC. (Answer 0.81 mm)

2. A steel ring is 50 mm diameter and 2 mm thick. It must be fitted onto a shaft 50.1 mm diameter. Calculate the temperature to which it must be heated in order to fit on the shaft. The initial temperature is 20 ^oC and the coefficient of linear expansion is 15 x 10^{-6} per ^oC. (Answer 133.3 K)

3. A stub shaft 85.2 mm diameter must be shrunk to 85 mm diameter in order to insert it into a housing. By how much must the temperature be reduced? Take the coefficient of linear expansion is 12 x 10^{-6} per ^oC. (Answer -195.6 K)

4. A tank contains 40 m^3 of oil at 10^oC. Calculate the volume at 40^oC given γ = 700 x 10^{-6} per ^oC (0.84 m^3)

5. Copper sheet covers a wall and has an area of 20 m^2 at 15^oC. What is the change in area when it is heated to 80^oC? β = 34 x 10^{-6} per ^oC. (44.2 x 10^{-3} m^2)

3. DURABILITY

CORROSION RESISTANCE

You will find much information and pictures at http://www.corrosion-doctors.org

OXIDISATION

Corrosion takes many forms and it would require a very large section to explain it. The following is a brief summary of the forms of corrosion that occur with materials.

Oxygen from the environment combines with the material to form a new substance, usually an oxide film on the surface. If the oxide film is easily removed to expose new material, the process will continue until all the material is oxidised. In the case of most ferrous materials the oxide film is rust and this lets water through and crumbles away. In the case of copper and aluminium, the oxide film is durable and forms a protective coat on the surface. Materials like Gold and Silver do not oxidise easily but important engineering materials that resist oxidation are zinc, chromium, cadmium and others.

ELECTROLYTIC ACTION – BI METAL CORROSION

There are other factors that affect corrosion. The presence of water, especially if it contains salt, will enable electrolytic action to occur and greatly accelerate the process. This is greatly accelerated if there are two different metals present to create an electrolytic cell and so care must be taken when different metals are used in an assembly. The compatibility of metals is listed as the Electrode Potential (in volts) and the further apart two metals are in the table, the worse the electrolytic action.

TABLE OF ELECTRODE POTENTIAL IN VOLTS

Lithium	-3.02	Gold	+1.68
Potassium	-2.92	Nickel	-0.23
Sodium	-2.71	Tin	-0.14
Magnesium	-2.34	Lead	-0.12
Aluminium	-1.66	Hydrogen	0.00
Zinc	-0.76	Copper	+0.34
Iron	-0.44	Mercury	+0.8
Cobalt	-0.29	Silver	+0.8

Components and structures are often treated or coated to reduce corrosion. Here is a list of some of the preparatory treatments and coatings used for metals.

TREATMENT

- ***Pickling***
- ***Degreasing.***
- ***Wire brushing***
- ***Shot and vapour blasting***
- ***Flame descaling***
- ***Abrasive finishing***
- ***Polishing***
- ***Barrelling***

PROTECTIVE COATINGS

- ***Galvanising***
- ***Sherardising***
- ***Calorising***
- ***Chromising***
- ***Chromating***
- ***Phosphating***
- ***Metal Spraying***
- ***Cladding***
- ***Anodising***
- ***Electroplating***
- ***Plastic Coating***
- ***Paint Coating***

CHEMICAL ATTACK

Metals may be degraded by a variety of chemicals such as acids and alkali and these must always be considered.

Polymers do not corrode but may be prone to attack from other chemicals such as SOLVENTS which dissolves them away.

Ceramics are in the main resistant to most forms of chemicals and this is why they have been used for containers down the centuries.

POROSITY

We should mention here the importance of porosity. If a material allows liquid or gas to seep through it then this may cause problems such as contamination of food stuffs. On the other hand, porosity is necessary for a material used as a filter.

DIMENSIONAL STABILITY

We should also mention dimensional stability here. A material subjected to prolonged heat, cold, pressure and stress may change its dimensions and shape (e.g. creep covered in a later tutorial). Plastic bottles containing pressurised fizzy drinks should not change their shape over its intended shelf life.