ENGINEERING COUNCIL
CERTIFICATE LEVEL

ENGINEERING MATERIALS C102

TUTORIAL 2 – THE STRUCTURE OF MATERIALS

OUTCOMES

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

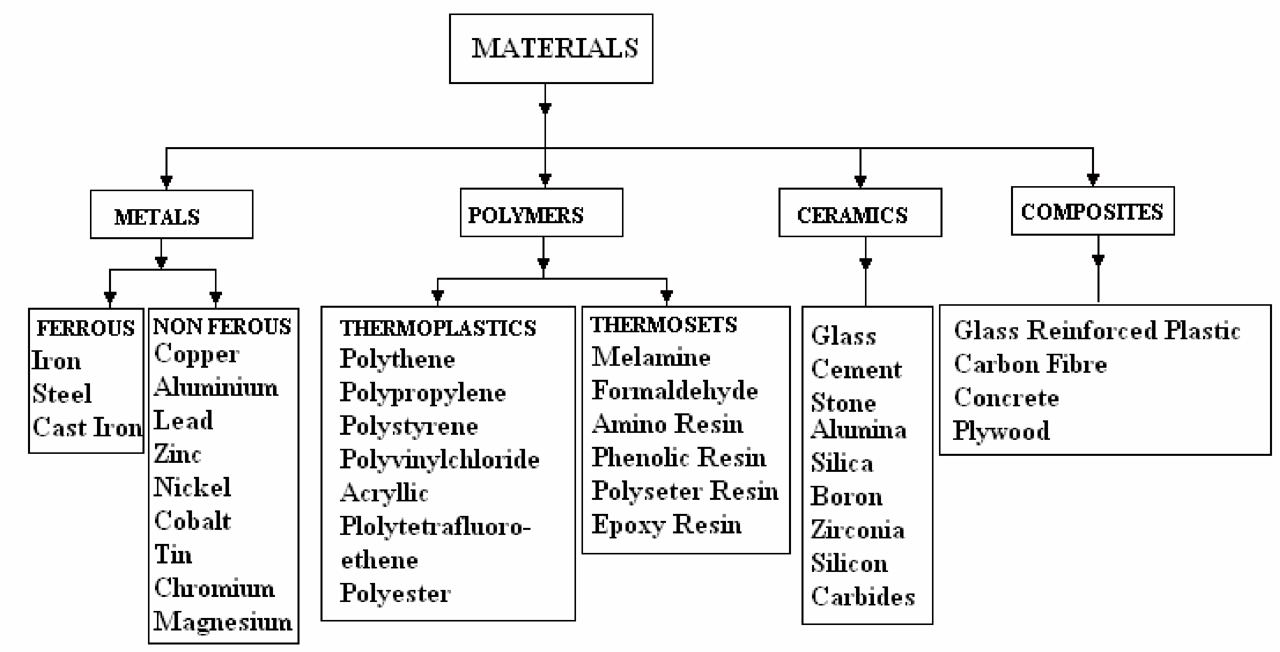
1. Recognise the structures of metals, polymers and ceramic materials.
2. Assess the mechanical and physical properties of engineering materials
3. Understand the relationships between the structure of a material and its properties.
4. Select materials for specific engineering applications.

CONTENTS

One of the most useful websites for finding materials is www.matweb.com

1. INTRODUCTION TO MATERIAL CLASSIFICATION AND TERMINOLOGY

Engineering materials may broadly be classed in FOUR groups - metals, polymers, ceramics and composites. Each class has sub groups and there are other special materials that don't fall into any of them. The chart shows a selection of materials and sub groups.



STRUCTURE

The structure of solid materials is either crystalline or amorphous. We can also have mixtures of materials glued together in a matrix.

CRYSTALLINE

Many materials crystallise when cooled slowly e.g. sugar and salt. As solidification occurs the molecules bond together in regular patterns to form individual crystals or grains that join with other similar crystals at the boundary. When processed, the crystals may be aligned or elongated in one direction producing different properties in different directions.

AMORPHOUS

This is a structure with no crystals and often results from rapid cooling. For example molten sugar poured onto a cold surface forms an amorphous glass like structure instead of crystallising. The structure is uniform with the molecules having random positions within it. The mechanical properties are usually the same in all directions.

Liquids are amorphous and when a metal melts, it changes from a crystalline structure into an amorphous liquid.

Materials may exist in a pure form or in some other form in a combination with other materials. How atoms and molecules stick together largely depend on its atomic structure and you should study this next.

2. METALS

Metals are of great importance in engineering because they possess so many properties that are needed to make components and structures such as conductivity and ductility. These properties are covered in the next tutorial. The metallic elements are classed as Iron (Ferrous) or not Iron (non – Ferrous). Any alloy containing iron is termed Ferrous. Let's start by examining materials with iron in them.

2.1 FERROUS MATERIALS

Iron ore is quite abundant and relatively cheap and can be made into a variety of iron based materials with many uses in structural and mechanical engineering. Iron is produced by melting the ore and other materials in a blast furnace and then refining it. In the early stages it contains many impurities including Carbon which has a dramatic affect on its properties. Pure iron is very difficult to produce and it is rarely used on its own. Iron is one of the few substances that are magnetic.

CAST IRON

In the early stages of refining the iron contains a lot of carbon and this makes it very fluid in the molten state so it was cast into ingots and then processed.

Historically, cast iron was one of the first materials to be used for large scale structures. The carbon forms as graphite flakes and this makes the material very brittle but it is good for casting complex shapes. It does not rust easily so it is used to make decorative outdoor structures such as garden furniture. Cast iron breaks very easily but when used in compression it is strong so it was widely used for making columns, pillars and arch bridges. Victorian shopping arcades had delicate cast arches and reached its grandest level in the construction of the Crystal Palace.

Graphite makes a good solid lubricant and so machined cast iron slides ways in machine tools are normal.

WROUGHT IRON

Wrought iron was another traditional material from the early times. It is produced by repeatedly heating strips, stretching it and folding it. This disperses the carbon and produces a material with properties similar to pure iron. Being difficult to make it is expensive and mainly finds use in wrought iron gates and similar structures because it can be bent and shaped into decorative shapes.

CARBON STEELS

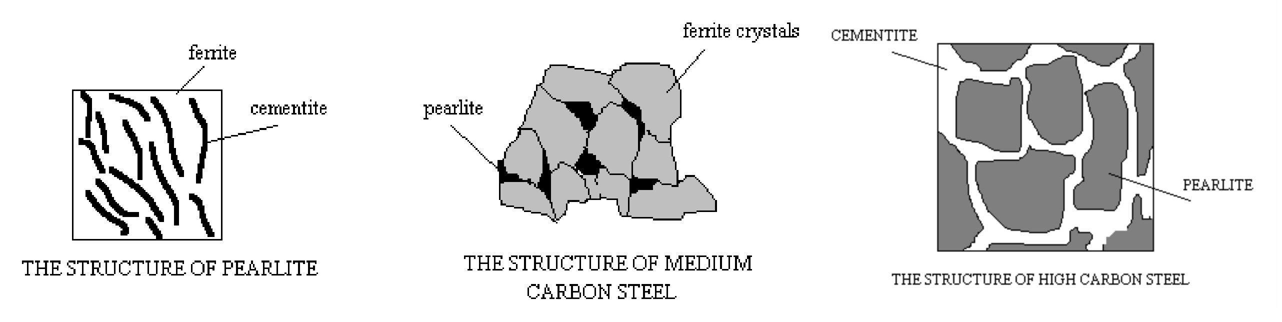
Steel is an alloy of iron and other elements that gives it the required properties. One of the most important elements is carbon. Pure iron is almost unknown as carbon always gets into it during the manufacturing stage when the ore is melted with coke.

Steels with carbon fall between the extremes of pure iron and cast iron and are classified as follows.

NAME	CARBON CONTENT %	TYPICAL APPLICATION
Dead mild	0.1 – 0.15	pressed steel body panels
Mild steel	0.15 – 0.3	steel rods and bars
Medium carbon steel	0.5 – 0.7	forgings
High carbon steels	0.7 – 1.4	springs, drills, chisels
Cast iron	2.3 – 2.4	engine blocks

STRUCTURE

All metals form crystals when they cool down and change from liquid into a solid. In carbon steels, the material that forms the crystals is complex. Iron will chemically combine with carbon to form ***IRON CARBIDE*** (Fe_3C). This is also called ***CEMENTITE***. It is white, very hard and brittle. The more cementite the steel contains, the harder and more brittle it becomes. When it forms in steel, it forms a structure of 13% cementite and 87% iron (ferrite) as shown. This structure is called ***PEARLITE***. Mild steel contains crystals of iron (ferrite) and pearlite as shown. As the % carbon is increased, more pearlite is formed and at 0.9% carbon, the entire structure is pearlite.



If the carbon is increased further, more cementite is formed and the structure becomes pearlite with cementite as shown.

ALLOY STEELS

Besides carbon, iron is alloyed with other elements to produce desirable properties. One important group is ***Stainless Steel.*** The name covers a wide range of steel types and grades for corrosion or oxidation resistant applications. Stainless steels are iron alloys with a minimum of 10.5% chromium. Other alloying elements are added to enhance their structure and properties these being Nickel, Molybdenum, Titanium and Copper

SELF ASSESSMENT EXERCISE No. 1

Conduct further research and then sketch and describe the crystal structure of cementite (e.g. http://www.msm.cam.ac.uk/phase-trans/2003/Lattices/cementite.html)

2.2 NON FERROUS METALS

There are a large number of metals with various properties that make them important. Here is a brief list of some of them with some of their properties.

COPPER
- red colour.
- a good conductor of heat and electricity and widely used for electrical components.
- good corrosion resistance.
- malleable and ductile and easily drawn into wire and tube.
- easily joined by soldering.

ALUMINIUM
- white colour
- not as good as copper for conducting electricity but cheaper and often used instead of copper.
- good corrosion resistance.
- can be made into light and strong aluminium alloy and is used for many structural components.
- easily rolled into thin sheets and foil.
- often extruded into various sections for light structures.

LEAD
- bluish grey colour.
- very heavy (Dense). Used for screening from radiation.
- soft.
- good corrosion resistance.
- added to other metals to make them more machineable.
- added to tin it makes solder.

TIN
- silvery white colour.
- good corrosion resistance and used to coat other metals.
- widely alloyed with other metals e.g. to make bearings.

ZINC
- bluish white colour.
- good corrosion resistance.
- used to coat steel sheets and components such as nails (galvanised).
- widely alloyed with other metals to make a good casting material..

SILVER
- the best electrical conductor of all but too expensive for making wires and cables.
- mainly used for jewellery.

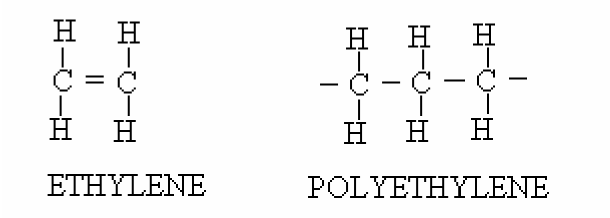
GOLD
- very resistant to oxidisation and used for coating electrical contacts in high quality switches.
- mainly used for jewellery.

PLATINUM
- better than gold but more expensive
- mainly used for jewellery.

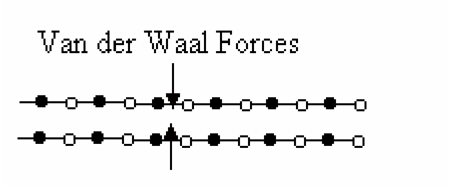
ALLOYS
Some of the alloys formed by these metals are :
Brass – mainly Copper and Zinc.
Bronze – mainly Copper and Tin and often with Phosphor added.

3. **POLYMERS AND ELASTOMERS**

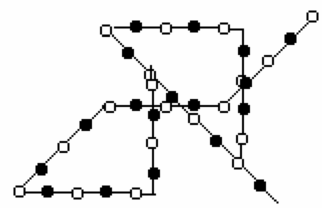
Materials generally known as plastics and rubbers are made from organic molecules based on carbon. The molecules are made from long chains of atoms. The long chains start off as individual molecules called monomers and in production they link up to form the polymer. Consider how the monomer ***ethylene*** is turned into the polymer ***polyethylene*** (polythene). The hydrocarbon molecule ethylene (C_2H_4) has a double bond between the two carbon atoms. This can be changed into single bonds that join it to a carbon on both sides to form a chain.



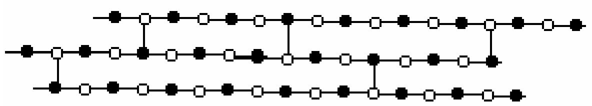
The atoms are joined with strong covalent bonds. The molecules are attracted to each other by Van der Waal forces and if the chains lay parallel, these can be quite strong.



The chains can become tangled.



Molecules can also become cross-linked and this changes their properties.



Depending on the exact molecule and the form it takes, polymers can be classified into three groups.

THERMOPLASTIC

Heating the polymer vibrates the molecules and if they are not cross linked, the distance between the molecules will increase and the Van der Waal forces will be reduced. This will make the polymer soften so these types and be remoulded by heating.

THERMOSETTING

During the moulding process, chemical changes occur and the molecules become cross-linked forming a more rigid structure. Reheating will not soften the polymer.

ELASTOMERS

These are virtually the same as thermosetting but they have a very high degree of elasticity and although they stretch easily compared to metals, they spring back into shape. The tangled molecules tend to straighten when pulled but spring back when released.

GENERAL PROPERTIES

Polymers are often referred to as plastics because they often have a very large plastic range. This is not always the case and polymers exhibit a wide range of mechanical properties (strength, toughness and hardness etc.) In general polymers are very resistant to attack from chemicals reagents. They have a low density compared to materials and so for example, a plastic bottle is much lighter than a glass bottle of equivalent strength. They can be coloured or transparent and give a pleasing finished appearance to many household items. These properties make them suitable for a wide range of manufactured items such as:

- Plastic tubes/pipes
- Bottles
- Car shells/interior linings
- Cases for electronic goods
- Springs/shock absorbers
- Tool handles/cases
- Toys
- Electric wire insulation
- Seals used in hydraulics and pneumatics.
- Packaging.
- Linings to vessels.

Useful web sites

www.Vakoseals.com
www.Matweb.com
http://www.efunda.com/materials/polymers/history/history.cfm?list_order=time

MONOMER

A monomer is a single molecule which when joined to others of the same kind in a chain is called a Polymer.

CO-POLYMERS

These are long chain molecules made up of different monomer joined together in a regular pattern. An example is polyvinyl chloride that has alternate molecules of vinyl chloride and vinyl acetate.

THE MICROSTRUCTURE OF POLYMERS

When metals solidify we see a crystalline structure form as the small molecules move easily into regular shapes with ionic bonds holding them together. Polymers have long chain molecules entangled with each other and this makes it difficult for them to move and form a crystalline pattern. The solidification process of polymers may produce some regions in crystalline form and these are called crystallites. The rest of the material is amorphous. The crystalline region can be as much as 90% in some polymers.

MELTING

Metals and other crystalline materials melt at a fixed temperature but amorphous materials tend to soften and become more like a viscous liquid. If a polymer has a large crystalline content, the change from crystalline to amorphous structures when it melts is accompanied by an increase in the volume. The temperature at which this occurs is denoted T_m. Generally, the melting point increases in temperature with the degree of crystallinity.

GLASS TRANSITION TEMPERATURE

Polymers are generally soft at normal temperatures but they can become hard and brittle when cooled. The temperature at which it changes from soft and flexible to hard and glassy, is called the glass transition temperature denoted T_g. Some polymers are hard and rigid at normal temperatures and these have many uses.

SELF ASSESSMENT EXERCISE No. 2

List at least three manufactured products that are made from thermoplastics.

List at least three manufactured products that are made from thermosets.

List at least three manufactured products that are made from elastomer.

4. CERAMICS

The word "ceramic" is traced to the Greek term Keramos, meaning pottery or potter. Ceramics are defined as products made from inorganic, non-metallic materials with a crystalline structure, usually processed at a high temperature at some time during their manufacture.

Ceramics may be crystalline (e.g. diamond) or amorphous (e.g. glass). They may be broken into small particles and bonded into a matrix (e.g. a grinding wheel). Whilst Bricks, Pottery, Glass and so on are widely used for every day objects, modern ceramics for engineering components have been produced for the following purposes.

- **HIGH MELTING POINT** – e.g. furnace linings.
- **HIGH HEAT ABSORPTION (specific heat capacity)** e.g. space shuttle tiles and storage heaters.
- **HARDNESS** – e.g. cutting tools such as Tungsten Carbide tips and grinding wheels.
- **LOW CREEP AND THERMAL EXPANSION** – e.g. turbine blades where any elongation would wreck the engine.
- **POROSITY** – e.g. used to make very tight filters whose absolute filtration rating is too tight to allow the passage of bacteria and pathogens like cryptosporidium. Such filters are used in survival kits for filtering urine and making it drinkable.
- **ELECTRONIC PROPERTIES** – e.g. used in semi conductors and microelectronics as parts of components, substrate, or package.
- **ELECTRIC PROPERTIES** – e.g. used for insulators on high power transmission lines.

Here is a list of some of the modern ceramics materials.

Alumina, Zirconia, Silicon Carbide, Silicon Nitride, Boron Carbide, Beryllia, Steatite and Sterite.

GLASS

The main constituent of most commercial glass is sand in other words - SILICA. This is mixed with other substances to produce the required properties.

A typical composition of glass is :
70% - 74% SiO_2 (silica)
12% - 16% Na_2O (sodium oxide)
5% - 11% CaO (calcium oxide)
1% - 3% MgO (magnesium oxide)
1% - 3% Al_2O_3 (aluminium oxide)

SELF ASSESSMENT EXERCISE No. 3

1. Visit http://www.dynacer.com and then :
   Name and describe three components made from ceramics for electronic purposes.
   Name and describe three components made from ceramics for their thermal properties.
   Name and describe three components made from ceramics for their biological properties.
   Name and describe three components made from ceramics for their refractory properties.

2. Metals, polymers and ceramics usually show a dominant from of bonding. Explain which type of bonding is normally seen in each class of materials and explain how this type of bonding gives rise to the typical values of strength, stiffness and conductivity seen in these materials.

5. COMPOSITES

A composite material is a combination of two or more materials to obtain the best properties of both. There are broadly two classifications.

PARTICLE COMPOSITES

This is a material in which particles of one material is fixed in a matrix of another. Here are some examples.
Cermets - Particles of very hard ceramic materials are embedded in a metal to produce cutting tools and dies. For example, tungsten carbide embedded in cobalt makes a very hard cutting tool and dies. They can be compacted into the required shape and then heated to sinter them. This means the cobalt is hot enough to re-crystallise and form a matrix around the tungsten.
Mortar and Concrete – sand, gravel and stone are bonded into a matrix of cement that sets and forms a light material strong in compression. Since it can be moulded or laid down wet, it is an ideal building material.
Tarmac – a matrix of gravel held in a matrix of tar, ideal for roads.

FIBRE COMPOSITES

Examples are :

- Reinforced concrete.
- Glass reinforced plastics (GRP)
- Carbon fibres.
- Aramid fibres.

Concrete is very brittle and weak in tension so it is normally only used for support type structures (columns and solid floors). By adding steel rods, the structure becomes stronger in tension and withstands some bending. Hence bridges, unsupported floors and other structures where some bending occurs can be made to take the tension. The resulting structure is lighter than steel on its own.

Glass and carbon fibres when made new are very strong and flexible and if they are imbedded in a matrix of plastic (thermosetting) they retain their high tensile strength. The result is a very strong flexible and light structure. Many things are made from these materials such as boat hulls, tennis rackets, fishing poles and so on.

Brittle materials fail by cracks spreading through them with little resistance. Adding fibres prevents the crack opening and spreading.

There are also natural fibre composites such as wood.

Consider a cylindrical rod made with fibres and a matrix material. Let the volume of the fibre be V_f and the volume of the matrix be V_m. The volume of the resulting composite is $V_c = V_f + V_m$.

The mass of the fibre is $m_f = \rho_f V_f$
The mass of the matrix is $m_m = \rho_m V_m$
The mass of the composite is $m_c = \rho_c V_c = \rho_f V_f + \rho_m V_m$

$$\rho_c V_c = \rho_f V_f + \rho_m V_m = \rho_f V_f + \rho_m (V_c - V_m)$$

$$\rho_c = \rho_f \frac{V_f}{V_c} + \rho_m \frac{V_c - V_f}{V_c} = \rho_f \frac{V_f}{V_c} + \rho_m \left(1 - \frac{V_f}{V_c}\right)$$

The ratio $V_f/V_c = r_f$ is the volume fraction of the fibre. $1 - V_f/V_c = 1 - r_f = r_m$ is the volume fraction of the matrix. $\rho_c = \rho_f r_f + \rho_m r_m$

WORKED EXAMPLE No.1

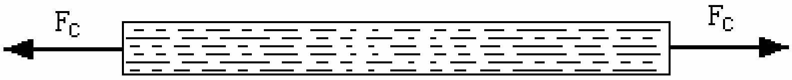
A GRP contains 70% glass fibre by volume. The glass has a density of 2100 kg/m^3 and the resin has a density of 1300 kg/m^3. Calculate the density of the resulting composite.

SOLUTION

$V_f/V_c = r_f = 0.7$ $1 - V_f/V_c = r_m = 0.3$
$\rho_c = 2100 \times 0.7 + 1300 \times 0.3 = 1860$ kg/m^3

STRENGTH OF FIBRE COMPOSITES

Consider a cylinder of composite material subjected to a tensile force.



The force in the composite F_c is the sum of the force taken by the fibres F_f and the matrix F_m. This is only true if the fibres are firmly bonded to the matrix and do not slip. $F_c = F_f + F_m$

For each material the force is the stress (σ) x area (A) hence $\sigma_c A_c = \sigma_f A_f + \sigma_m A_m$
Divide through by A_c and $\sigma_c = \sigma_f A_f/A_c + \sigma_m A_m/A_c$
The ratio A_f/A_c is the volume fraction r_f and A_m/A_c is the volume fraction r_m
Hence $\sigma_c = \sigma_f r_f + \sigma_m r_m$

WORKED EXAMPLE No.2

$r_f = 0.4$ $r_m = 1 - 0.4 = 0.6$ $\sigma_f = 3.4 \times 10^9$ N/m^2 $\sigma_m = 60 \times 10^6$ N/m^2

$\sigma_c = \sigma_f r_f + \sigma_m r_m = 5 \times 10^9 \times 0.4 + 60 \times 10^6 \times 0.6 = 2.04 \times 10^9$ N/m^2 = 2.04 GPa

LAMINATES

An important type of composite material is those made up from laminated layers of either the same or different materials glued to each other in layers to obtain an overall structure with the combined properties of each layer.

PLYWOOD
Grainy materials like wood have strength in one direction only so if they are layered with the grain at 90^o to each other, equal strength is obtained in both.

TYRES
An ideal tyre must have strength, good grip, not wear and not puncture. For this reason a tyre consists of laminated layers of Rayon, Nylon and Steel in a rubber matrix with cross plies to produce strength in all directions.

SELF ASSESSMENT EXERCISE No. 4

1. A GRP contains 60% glass fibre by volume. The glass has a density of 2100 kg/m^3 and the resin has a density of 1300 kg/m^3. Calculate the density of the resulting composite. (1780 kg/m^3)

2. A rod of composite material contains 30% carbon fibre by volume. The tensile strength of the fibre is 3.5 GPa and the tensile strength of the resin is 60MPa. Calculate the tensile strength of the composite. (1.092 GPa)