EDEXCEL NATIONAL CERTIFICATE

UNIT 10: PROPERTIES AND APPLICATIONS OF ENGINEERING MATERIALS

NQF LEVEL 3

OUTCOME 1 – TUTORIAL 3
POLYMERS, CERAMICS AND SMART MATERIALS

Unit content

1 Be able to describe the structure of and classify engineering materials

Atomic structure: element; atom e.g. nucleus, electron; compound; molecule; mixture; bonding mechanisms e.g. covalent, ionic, metallic

Structure of metals: lattice structure; grain structure; crystals; crystal growth; alloying e.g. interstitial, substitutional; phase equilibrium diagrams e.g. eutectic, solid solution, combination; intermetallic compounds

Structure of polymeric materials: monomer; polymer; polymer chains e.g. linear, branched, cross-linked; crystallinity; glass transition temperature

Structure of ceramics: amorphous; crystalline; bonded Structure of composites: particulate; fibrous; laminated

Structure of smart materials: crystalline; amorphous; metallic

Classification of metals: ferrous eg plain carbon steel, cast iron (grey, white, malleable, wrought iron), stainless and heat-resisting steels (austenitic, martensitic, ferritic); non-ferrous eg aluminium, copper, gold, lead, silver, titanium, zinc; non-ferrous alloys e.g. aluminium-copper heat treatable – wrought and cast, non-heat-treatable – wrought and cast, copper-zinc (brass), copper-tin (bronze), nickel-titanium alloy

Classification of non-metals (synthetic): thermoplastic polymeric materials e.g. acrylic, polytetrafluoroethylene (PTFE), polythene, polyvinyl chloride (PVC), nylon, polystyrene; thermosetting polymeric materials e.g. phenol-formaldehyde, melamine-formaldehyde, urea-formaldehyde; elastomers; ceramics e.g. glass, porcelain, cemented carbides; composites e.g. laminated, fibre reinforced (carbon fibre, glass reinforced plastic (GRP), concrete, particle reinforced, sintered; smart materials e.g. electro-rheostatic (ER) fluids, magneto-rheostatic (MR) fluids, piezoelectric crystals

Classification of non-metals (natural): e.g. wood, rubber, diamond

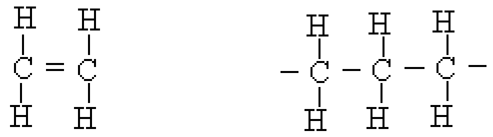
CONTENTS

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

Most of the self assessment for this tutorial is in the form of separate assignments.

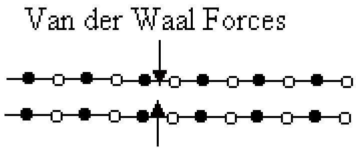
1. POLYMERS AND ELASTOMERS

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.

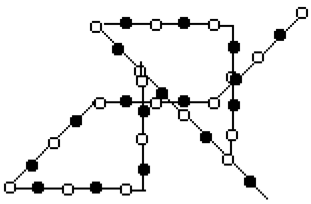


ETHYLENE POLYETHYLENE

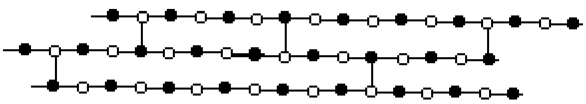
The atoms are joined with strong covalent bonds. The molecules are attracted to each other by Van der Waal forces and if the chains lay parallel, these can be quite strong.



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

The raw material is in the form of soft dough like substance often in sheet form. They set into a hard state by initiating a chemical reaction either by heating them or mixing them with a catalyst. This process called ***curing*** makes 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 chemical reagents. They have a low density compared to other 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. 1

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.

2. 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. 2

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.

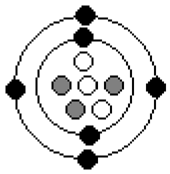
Name and describe three components made from ceramics for their biological properties.

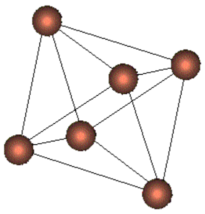
Name and describe three components made from ceramics for their refractory properties.

NATURAL NON-METALS

CARBON deserves a special mention. It exhibits some metallic properties (reasonable conductor) and in diamond form is the hardest known material. In fibre form it makes a very strong material used in composites. Used with iron it has a dramatic affect on the mechanical properties.

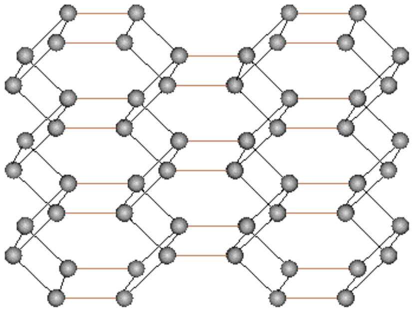
Carbon can form 2 different types of crystals, diamond and graphite. A third type called ball carbon has been found but does not appear to form naturally. Carbon has an atomic number of 6 and a mass of 12. There are 6 electrons so there must be four electrons missing from the second shell. This means there are four bonds or valences to be used up when it joins with other atoms.





In the diamond form each atom forms a covalent bond with four other atoms to form a tetrahedral structure. This pattern is also repeated for every atom at the corner. The bonding is equally strong in all directions and this makes the strongest hardest material known.

In the graphite form, the carbon atoms form flat hexagonal crystals as shown with each atom bonding with 3 in the same plane and one above and one below. This leaves each with a free electron resulting in slippery layers loosely held together by the electrons. This makes it suitable for dry lubrication and also enables it to conduct electricity.



WOOD is something we think of a coming from trees and has many engineering uses. It has a hard, fibrous structure and is a natural composite material. It may have a fine hard structure or a soft weak structure depending on the type of tree. It can be used for structures or turned into other materials such as paper and used for a wide range of things such as filters. Because of its fibrous nature, wood is stronger in one direction than the other. This is overcome in plywood where sheets are bonded together with the grain laid in different directions.

RUBBER is a naturally occurring elastomer known as latex and obtained by tapping the sap from rubber trees. The use of rubber is widespread, ranging from household to industrial products either in its natural or processed state. Tires and tubes are the largest consumers of rubber.

SELF ASSESSMENT EXERCISE No. 3

1. Describe the main uses of diamonds for engineering and manufacturing applications.

2. Find out what is done to wood to make it bend without breaking e.g. for boat planks and furniture parts) and also to allow it to be cut into thin sheets for veneers and plywood?

3. List some products made largely from natural rubber. What advantages does natural rubber have over polymers?

3. 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.

Sintering is a process where powder is poured into the mould and pressed with a die into the required shape. The powder is heated and pressurised so that the particles fuse. The structure produced is porous because granules do not melt completely but become sintered leaving gaps between them. The process may produce a course sinter or a fine sinter. Bronze bearing bushes which retain lubricants in the porous structure are produced this way. Steel components such as shaft couplings are made this way. Very hard materials such as tungsten carbide may be formed into cutting tool tips by this method.

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.

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

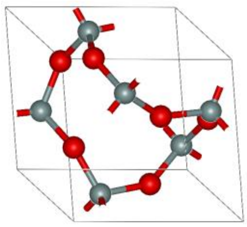
An ideal tyre must have strength, good grip, not wear and not puncture. For this reason a tyre consists of laminated layers of Rayon, Nylon and Steel in a rubber matrix with cross plies to produce strength in all directions.

4. SMART MATERIALS

You may come cross materials like "funny putty" that can be stretched and squashed easily like clay or plasticine but when thrown against a hard surface it bounces like a hard ball. When squashed rapidly the material becomes very stiff and changes its plasticity. There are many materials that change their physical properties in a controlled manner in response to some action like applying a stress, exposing it to light, magnetism or an electric charge.

PIEZOELECTRIC materials are materials that change shape when a voltage is applied to it so if an alternating voltage is applied it can be made to emit sound. It works in reverse and produces a voltage when stressed in various ways and so is used to make microphones and instruments such as pressure transducers.

The material is mainly crystalline ceramics and the most common one is called QUARTZ which is Silicon Dioxide (SiO_2). Silicon dioxide is the most abundant mineral in the Earth's crust. Sand is mainly composed of this and used to make glass. It occurs in many crystalline forms and is known as a polymorph, which means *many forms*. Quartz is mostly a trigonal crystal structure of SiO_2 shown in the picture. There are other materials mineral, biological and man made that exhibit piezoelectric properties.



ELECTRO-RHEOSTATIC (ER) FLUIDS change their viscosity in the presence of an electric field. This may be used to change a liquid into a gel or almost solid structure. The basic structure of these fluids is fine solid particles (colloidal) mixed and suspended in a fluid. ER fluids can be as simple as milk chocolate or cornstarch and oil. In a strong electric field, the particles are polarised like little magnets and form chains or columns parallel to the field. You can see a simulation at this link. http://www.ssslab.com/ehtml/3_1.php

MAGNETO-RHEOSTATIC (MR) FLUIDS change their viscosity in the presence of a magnetic field. This may be used to change a liquid into a gel or almost solid structure. MR fluid is composed of carbonyl iron particles, 'soft' iron particles which are only 3-5 μm in diameter, hydrocarbon oil and other additives to produce the required fluid properties. Applying a magnetic field forces the particles to line up so that the liquid becomes solid. The stronger the field, the more viscous the fluid becomes. Removing the magnetic field unlocks the particles and turns the solid back to liquid. MR fluids are being used in exercise machines, washing machines, car shock absorbers, and artificial legs.

SHAPE-MEMORY ALLOYS (SMA), is a metal alloy that "remembers" its original, cold-forged shape. When deformed beyond the yield point normal metals will stay deformed but SMA will return to the pre-deformed shape when it is heated. Imagine a car that can have its dents removed by simply heating the panel.

Alloys exhibiting this property are

- Copper/zinc/aluminium/nickel.
- Copper-aluminium-nickel.
- Nickel/Titanium.

You should have come across the terms ***Austenite*** and ***Martensite*** in tutorial 2 and learned that the terms also apply to other alloys. Alloys that have these two phases form the basis of SMA. It is found that Austenitic structures can be transformed into Martensitic structures by stress and strain as well as by heat. The crystalline changes produce distortion in the crystal lattice and dimensional changes in the bulk material. Heating can reverse this and this forms the basis of memory metals.

An important property of these alloys is that they are hard and springy above the transition temperature (the Austenitic form). Below the transition temperature they are soft and easy to bend (the Martensitic form).

NiTi alloys are more expensive. The transition from the martensitic phase to the austenitic phase is only dependent on temperature and stress, not time, as with carbon steel. The change does not involve the diffusion of atoms and it is reversible. This gives it the memory properties. While martensite can be formed from austenite by rapidly cooling carbon steel this process is not reversible, so steel does not have shape-memory properties.

SELF ASSESSMENT EXERCISE No. 4

1. Visit the web site http://webdocs.cs.ualberta.ca/~database/MEMS/sma_mems/smrt.html and any others. Produce a list of uses for:

   Piezoelectric crystals
   MR Fluids
   ER Fluids

2. Find out and list other smart materials than those above giving a brief description of each.

3. Find out and make a list of as many SMA alloys that you can find (e.g. list on Wikapedia)