

EDEXCEL NATIONAL CERTIFICATE

UNIT 12 – ENGINEERING MATERIALS OUTCOME 1

1. STRUCTURE AND CLASSIFICATION OF ENGINEERING MATERIALS

Metals: ferrous and non-ferrous metals and alloys e.g. cast irons, plain carbon steels, brasses, bronzes, aluminium alloys; crystal lattice, grain formation, interstitial and substitutional alloys, intermetallic compounds

Polymers: natural and man-made polymers: elastomers, thermosetting and thermoplastic polymers

Ceramics: amorphous, crystalline and bonded ceramics

Composites: particulate, fibrous and laminated composites

CONTENTS

1. Introduction to Materials Classification and Terminology

Metals, Polymers, Ceramics and Composites

Crystalline

Amorphous

2. Atomic Structures of Materials.

Atomic Structure

Types of Bonds

Crystal Lattices

Carbon

3. Metals

Ferrous

Non Ferrous

4. Polymers and Elastomers

Thermoplastic

Thermosetting

Elastomers

Monomers

Co-Polymers

5. Ceramics

Types and Definition

Summary of properties and Uses.

6. Composites

Particle

Fibre

Laminates

7. Further Studies

Solid Solutions

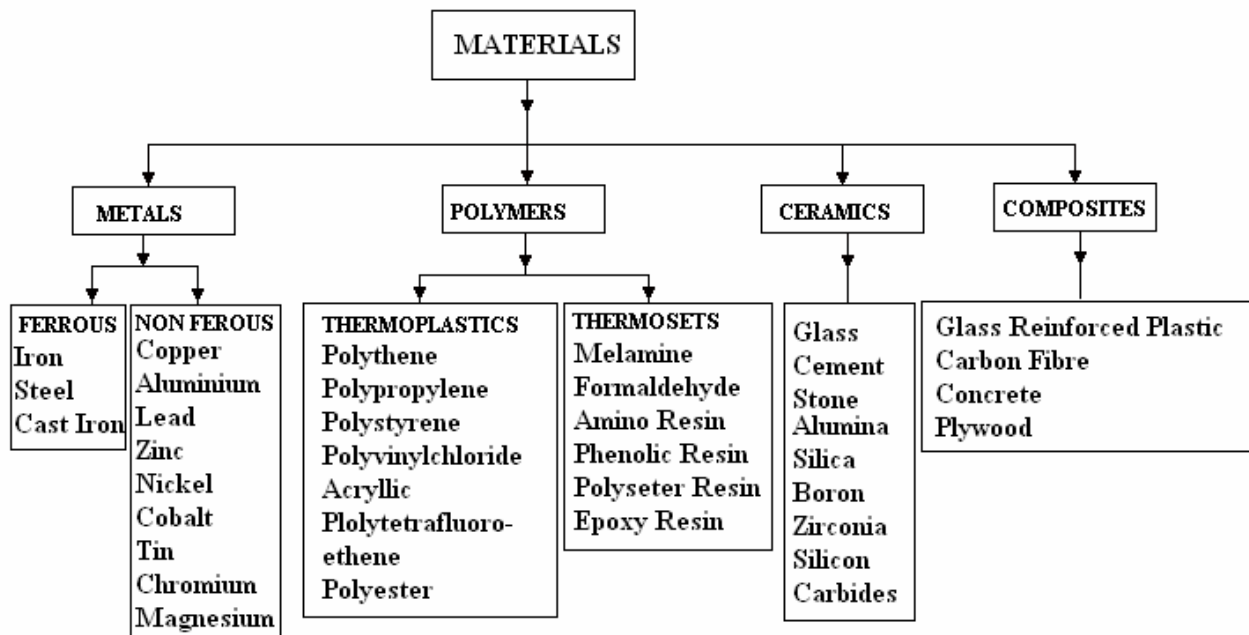
Thermal Equilibrium Phase Diagrams

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. 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.

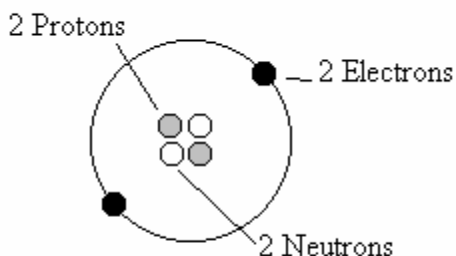
Liquids are amorphous and when a metal melts, it changes from a crystalline structure into an amorphous liquid.

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. ATOMIC STRUCTURES

All substances are made up from atoms. A substance made from only one type of atom is called an element. Often the atoms rearrange themselves into molecules containing two or more atoms either of the same substance or of more than one substance. There are 92 different elements occurring naturally. The smallest and simplest is the hydrogen atom and the largest is uranium.

THE STRUCTURE OF HELIUM



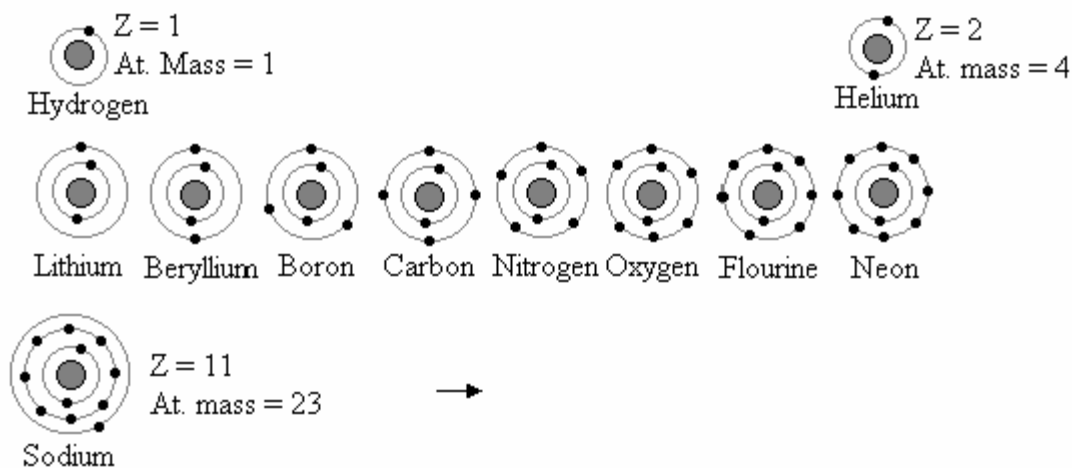
Atomic Number Z is 2

Atomic Mass is 4

An atom is made from three sub-atomic particles called electrons, protons and neutrons. The protons and neutrons are large compared to the electrons and clump together to form a nucleus. The protons carry a positive charge of electricity. The electrons carry a negative charge of electricity and they orbit the nucleus at various distances and form spherical shells. The force of attraction between positive and negative is ideally balanced by equal numbers of protons and electrons. The neutrons only affect the mass of the atom. The Atomic number Z is the number of protons. The atomic mass is the number of protons plus the neutrons. In a stable atom, the number of electrons equals the number of protons so that there is no resultant charge.

The numbers of electrons that form each shell do so in a fixed pattern. The innermost shell contains two electrons. The next shell contains eight electrons the third eight, the fourth eighteen and so on. It usually happens that there are insufficient electrons to complete the outermost shell and exactly balance the nucleus. For each possible combination we get an element.

The elements are arranged into a periodic table, part of which is shown below.



The first line of the table shows the possible combinations with only one shell and so contains only two elements. The first is Hydrogen with one electron in the first shell and so is incomplete. The second is Helium with two electrons in the first shell and so it is complete.

The second line shows all the possible eight arrangements with a complete inner shell. Only Neon has a complete outer shell.

The third line would show eighteen possible arrangements with a complete first and second shell. The table proceeds in this way up to the largest atom.

COMPLETE LIST OF THE ELEMENTS

At.no. (Z)	Symbol	Element	At.no. (Z)	Symbol	Element	At. No. (Z)	Symbol	Element
1	H	Hydrogen	36	Kr	Krypton	71	Lu	Lutecium
2	He	Helium	37	Rb	Rubidium	72	Hf	Hafnium
3	Li	Lithium	38	Sr	Strontium	73	Ta	Tantalum
4	Be	Beryllium	39	Yt	Yttrium	74	W	Tungsten
5	B	Boron	40	Zr	Zirconium	75	Re	Rhenium
6	C	Carbon	41	Cb	Niobium	76	Os	Osmium
7	N	Nitrogen	42	Mo	Molybdenum	77	Ir	Iridium
8	O	Oxygen	43	Tc	Technetium	78	Pt	Platinum
9	F	Fluorine	44	Ru	Ruthenium	79	Au	Gold
10	Ne	Neon	45	Rh	Rhodium	80	Hg	Mercury
11	Na	Sodium	46	Pd	Palladium	81	Tl	Thallium
12	Mg	Magnesium	47	Ag	Silver	82	Pb	Lead
13	Al	Aluminium	48	Cd	Cadmium	83	Bi	Bismuth
14	Si	Silicon	49	In	Indium	84	Po	Polonium
15	P	Phosphorus	50	Sn	Tin	85	At	Astatine
16	S	Sulphur	51	Sb	Antimony	86	Rn	Radon
17	Cl	Chlorine	52	Te	Tellurium	87	Fr	Francium
18	A	Argon	53	I	Iodine	88	Ra	Radium
19	K	Potassium	54	Xe	Xenon	89	Ac	Actinium
20	Ca	Calcium	55	Cs	Caesium	90	Th	Thorium
21	Sc	Scandium	56	Ba	Barium	91	Pa	Protactinium
22	Ti	Titanium	57	La	Lanthanum	92	U	Uranium
23	V	Vanadium	58	Ce	Cerium	93	Np	Neptunium
24	Cr	Chromium	59	Pr	Praseodymium	94	Pu	Plutonium
25	Mn	Manganese	60	Nd	Neodymium	95	Am	Americium
26	Fe	Iron	61	Pm	Promethium	96	Cm	Curium
27	Co	Cobalt	62	Sa	Samarium	97	Bk	Berkelium
28	Ni	Nickel	63	Eu	Europium	98	Cf	Californium
29	Cu	Copper	64	Gd	Gadolinium	99	Es	Einsteinium
30	Zn	Zinc	65	Tm	Terbium	100	Fm	Fermium
31	Ga	Gallium	66	Dy	Dysprosium	101	Md	Mendelevium
32	Ge	Germanium	67	Ho	Holmium	102	No	Nobelium
33	As	Arsenic	68	Er	Erbium	103	Lw	Lawrencium
34	Se	Selenium	69	Tm	Thulium			
35	Br	Bromine	70	Yb	Ytterbium			

BONDS

COVALENT BOND

Atoms with a complete outer shell are stable and can exist on their own. Atoms with an incomplete outer shell will attract any other atom with an incomplete shell. For example, hydrogen will attract another hydrogen atom to form a molecule consisting of two atoms that share a common electron in order to be stable. This molecule has a symbol H_2 to indicate there are two atoms. Helium, on the other hand, is stable and will happily exist as one atom.

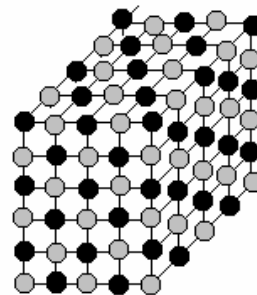
When atoms are joined by sharing one or more electrons, we call it a **covalent** bond. The same thing happens with oxygen that normally exists as O_2 and Nitrogen N_2 and so on.



ELECTROVALENT OR IONIC BONDING.

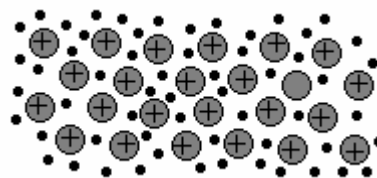
There are other ways that atoms join together. For example when a metal and non-metal come together, the non-metal might give up its electron to the metal. The metal becomes negatively charged and the non-metal positively charged. In this condition with extra or lost electrons, the atoms or molecules are called **IONS**. Ions attract each other like a pair of magnets and bond together. This is called **electrovalent** or **ionic** bonding. For example, consider Lithium and Fluorine. If the lithium gives up one electron to the fluorine, the fluorine has a full outer shell. The nucleus has a positive charge of 9 while the electrons total a negative charge of 10. The lithium is now missing an outer shell and has a nucleus with a positive charge of 3 and electrons with a negative charge of 2. The two nuclei have a difference of $9 - 3 = 6$ charges and so the two elements are pulled together.

For each case such as this, the two elements joint together in a pattern that satisfies the condition produced and in this case the fluorine atom must be surrounded by six lithium atoms and the lithium atom by six fluorine atoms. When they solidify, a fixed pattern or lattice forms that satisfies this condition and a crystal is formed. The 3D lattice is illustrated in the diagram and shows every atom is surrounded by six of the other type. This is the crystal lattice of lithium fluoride.



METALLIC BOND.

A third way of bonding occurs between the atoms of a metal. As the metal solidifies, the nucleus of each atom (being positive and unbalanced) all repels each other and consequently form a pattern (crystal). The nucleus is held in position by a swarm of electrons acting like glue between them. This is called the **metallic** bond. This theory explains why metals are good conductors of electricity as the cloud of electrons may be made to flow along a conductor when an electro motive force is applied.

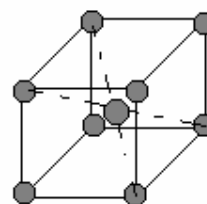


TYPES OF CRYSTALLINE STRUCTURES

There are seven types of crystals based on the shape of the basic lattice. These are called **triclinic**, **monoclinic**, **orthorhombic**, **tetragonal**, **cubic**, **rhombohedra** and **hexagonal**. Here are some of the structures found in crystalline metals. Sometimes the same material may exist in different crystalline forms and this is called **POLYMORPHISM**. The different forms are called **ALLOTROPES** and iron is one example with two allotropes called α iron and γ iron.

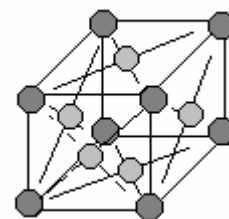
BODY CENTRE CUBIC (BCC)

The atoms arrange themselves with one at each corner and one right in the middle of the cubic space. This is the structure produced for solid chromium, α Iron and others.



FACE CENTRE CUBIC (FCC)

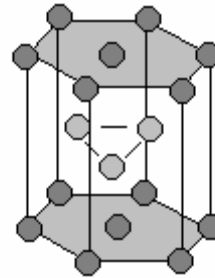
The atoms arrange themselves with one at each corner and one at the centre of each face. This is the structure of γ iron, aluminium, copper, gold and nickel.



HEXAGONAL CLOSED PACK (HCP)

Visualise the structure as an extruded hexagon with an atom at every corner plus three packed into the middle as shown. This is the structure of Magnesium and Zinc.

In these crystalline structures, each corner atom forms part of another structure and so the pattern is repeated throughout the crystal.



SELF ASSESSMENT EXERCISE No.1

Conduct further research and define the following. (e.g. http://www.chem.ox.ac.uk/icl/heyess/structure_of_solids/Lecture1/Lec1.html#anchor2)

- i. Lattice
- ii Motif
- iii Crystal Structure
- iv. Unit Cell
- v. Coordination Number

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.

3.1 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

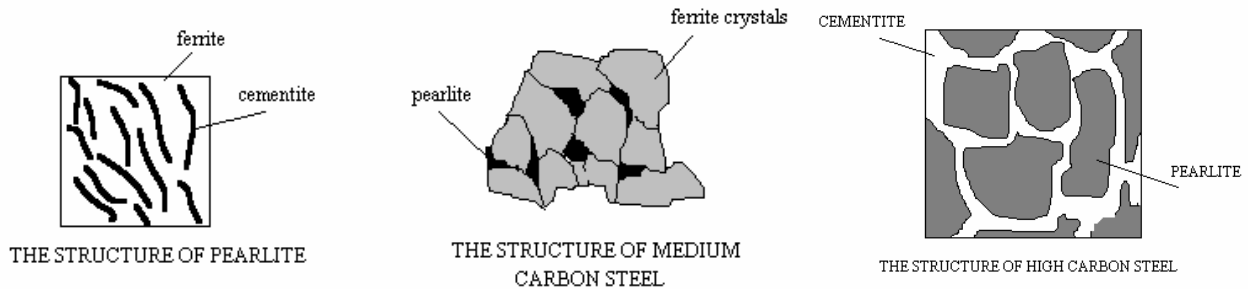
Steel is an alloy of iron and other elements that gives it the required properties. One of the most important elements is carbon. Pure iron is almost unknown as carbon always gets into it during the manufacturing stage when the ore is melted with coke.

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.2

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>)

3.2 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 oxidation 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

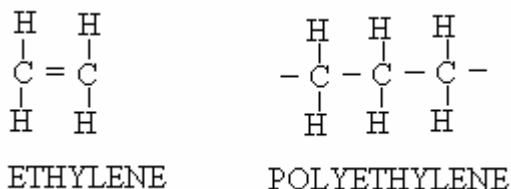
Some of the alloys formed by these metals are :

Brass – mainly Copper and Zinc.

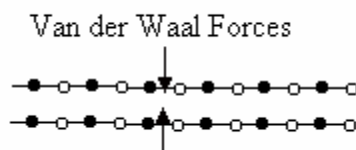
Bronze – mainly Copper and Tin and often with Phosphor added.

4. POLYMERS AND ELASTOMERS

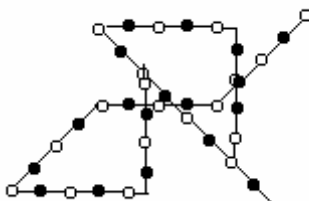
Materials generally known as plastics and rubbers are made from organic molecules based on carbon. The molecules are made from long chains of atoms. The long chains start off as individual molecules called monomers and in production they link up to form the polymer. Consider how the monomer *ethylene* is turned into the polymer *polyethylene* (polythene). The hydrocarbon molecule ethylene (C₂H₄) 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.



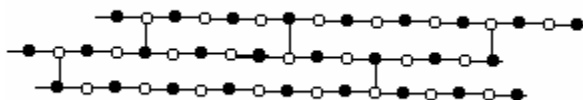
The atoms are joined with strong covalent bonds. The molecules are attracted to each other by Van der Waal forces and if the chains lay parallel, these can be quite strong.



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 can 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 chemical 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.3

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.

5. 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% SiO₂ (silica)

12% - 16% Na₂O (sodium oxide)

5% - 11% CaO (calcium oxide)

1% - 3% MgO (magnesium oxide)

1% - 3% Al₂O₃ (aluminium oxide)

SELF ASSESSMENT EXERCISE No.4

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.

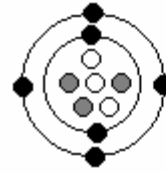
Name and describe three components made from ceramics for their biological properties.

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

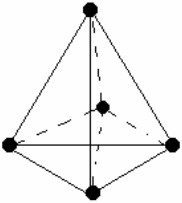
CARBON

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.

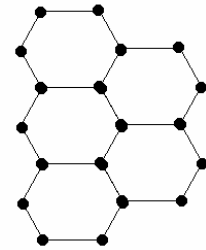


$Z = 6$
At. Mass = 12



In the diamond form each atom forms a covalent bond with four other atoms to form a tetrahedral structure. The atom in the middle is surrounded by four others. 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, only 3 bonds are formed with free electrons so the graphite forms into slippery layers loosely held together by the electrons. This makes it suitable for dry lubrication and also enables it to conduct electricity.



SELF ASSESSMENT EXERCISE No.5

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

6. 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

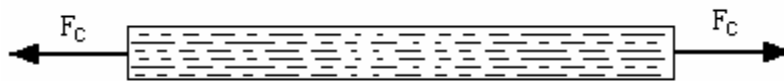
A GRP contains 70% glass fibre by volume. The glass has a density of 2100 kg/m^3 and the resin has a density of 1300 kg/m^3 . Calculate the density of the resulting composite.

SOLUTION

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

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

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

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

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° 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.6

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)

7. FURTHER STUDIES

The following is important for a good understanding of materials – especially metallic alloys. It is not clear whether this forms part of the module but it is certainly essential for Higher National studies and it would be a big advantage to study it now.

SOLUTIONS

When a substance dissolves in a liquid, the molecules of the substance leave the solid and become spaced between the molecules of the liquid. Salt and sugar will dissolve in water but sand will not. Sand is not soluble.

When salt is dissolved in water, the molecules of the salt fill the spaces between the molecules of the water and we have a liquid solution made from a liquid and a solid. There is a point at which no more salt can be dissolved because all the space is taken up and the solution is called SATURATED.

The amount of substance that can be dissolved before it becomes saturated depends upon the temperature. If we warm the water, we can dissolve more salt. If we cool a saturated solution, crystals will form of the dissolved substance. Interestingly, if we freeze salty water, on solidification, the salt will separate from the water so salt is not soluble in ice.

The substance being dissolved does not have to be a solid. A liquid may or may not dissolve in another liquid. When oil and water are mixed, the oil will not dissolve in the water but when alcohol and water are mixed, the alcohol will dissolve into the water. The same is true of molten metals. For example, molten lead and molten zinc will not dissolve. When cooled to a solid, they will form two separate layers.

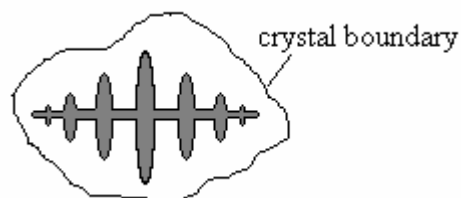
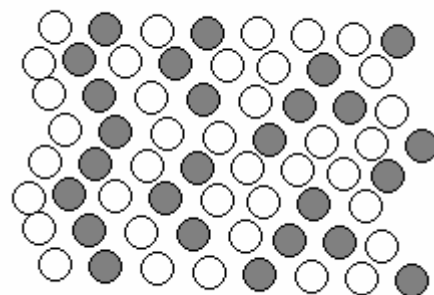
Sometimes the two substances will dissolve and remain dissolved when solidified such as carbon and iron or copper and aluminium.

SOLID SOLUTIONS

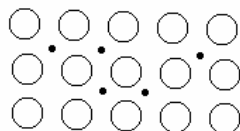
When the two substances remain as a solution after freezing, they are called solid solutions. This is most likely with metals when they have similar properties with atoms that are approximately of equal size as shown.

As the material solidifies, crystals form and these are made from both metals. The metal with the highest melting point will tend to solidify first so the core of the crystal has a higher concentration of one metal than the other.

The crystals initially form as a DENDRITE. This is a pattern like that of a snowflake.



In the case of a solid solution, the core of the dendrite has a concentration of one metal and the outer regions have a concentration of the other.

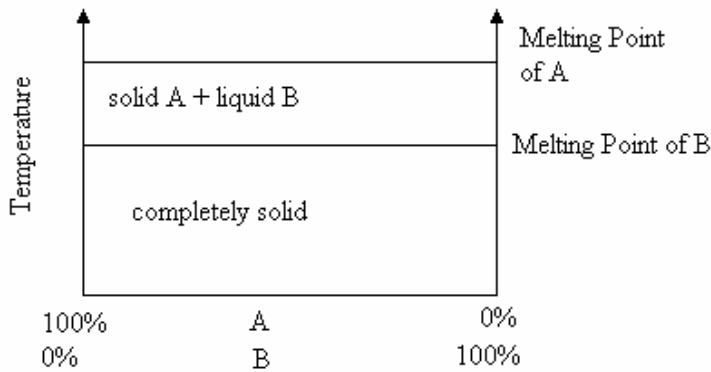


A solid solution will also form when one of the molecules of one is so small that it fits into the spaces between the larger molecules (called the interstitial spaces). This is what happens with carbon and iron.

THERMAL EQUILIBRIUM or PHASE DIAGRAMS

These are graphical representations of the various states of alloys and mixtures for various proportions and various temperatures. The resulting diagrams have varying degrees of complexity depending on the chemical compounds that form and the solubility of each substance in the solid and liquid states.

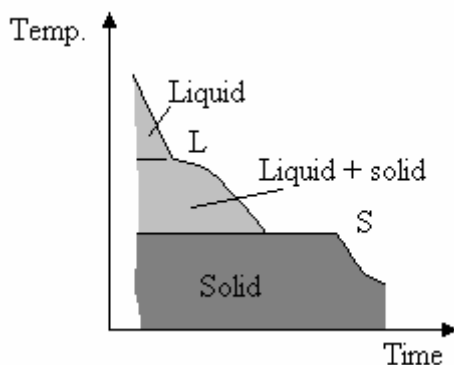
CASE 1 – A and B are Insoluble in Liquid and Solid State.



As the molten solution is cooled, the metal with the higher melting point will solidify first and then the metal with lowest melting point. They will form separate layers of the pure material. This will happen regardless of the proportion of each metal. A graphical representation of the process for all ratios of the two metals A and B is shown below.

CASE 2 - A and B are Soluble as Liquids but not as Solids.

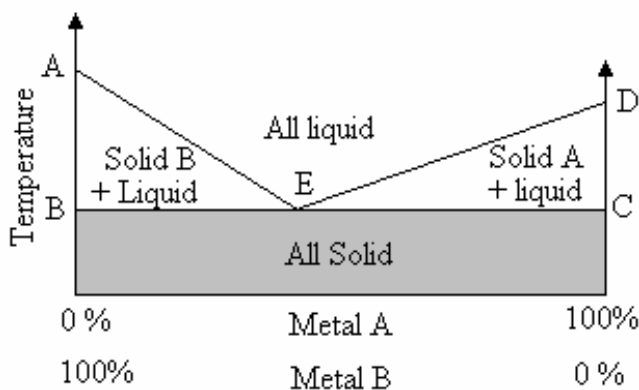
If we take a particular proportion and allow it to cool down from the liquid state we find that there are two pauses in the cooling rate at L and S. L is the temperature at which solidification starts and S is the temperature at which it ends. These temperatures vary according to the proportions of each metal. The melting point is depressed when two substances are mixed (e.g. salty water freezes below 0°C). This is true of metals in solution so temperatures L and S are not the melting point of either metal except when it is 100% of one or the other. If we measure the temperatures at L and S for various proportions and plot them, we can form the following phase or equilibrium diagram.



These temperatures vary according to the proportions of each metal. The melting point is depressed when two substances are mixed (e.g. salty water freezes below 0°C). This is true of metals in solution so temperatures L and S are not the melting point of either metal except when it is 100% of one or the other. If we measure the temperatures at L and S for various proportions and plot them, we can form the following phase or equilibrium diagram.

Above the line A E D everything is liquid and this line is called the **LIQUIDUS**. Everything below the line B E C is solid and this line is called the **SOLIDUS**. Point E is called the **EUTECTIC** point.

Consider what happens when a liquid solution to the left of E is cooled down. At some temperature metal B starts to solidify and forms dendrite crystals. The remaining liquid becomes richer in metal A and at some point the liquid will have a composition corresponding to point E and in fact goes slightly to the right of E. At this point metal A starts to solidify but this then makes the composition move to the left of E. Metal B then solidifies further and the composition swings back to the right of E and metal A solidifies. This continues until everything is solid. The resulting structure will be crystals of pure metal B and a laminate structure of metals A and B.



At some temperature metal B starts to solidify and forms dendrite crystals. The remaining liquid becomes richer in metal A and at some point the liquid will have a composition corresponding to point E and in fact goes slightly to the right of E. At this point metal A starts to solidify but this then makes the composition move to the left of E. Metal B then solidifies further and the composition swings back to the right of E and metal A solidifies. This continues until everything is solid. The resulting structure will be crystals of pure metal B and a laminate structure of metals A and B.

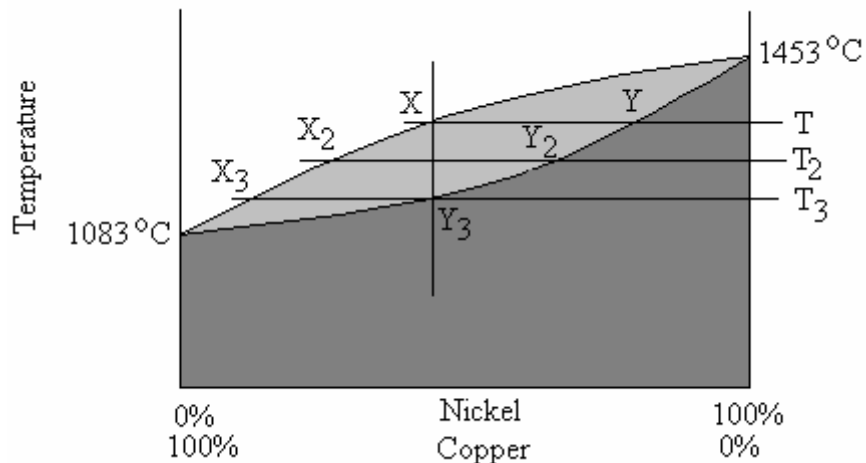
If we started to the right of E we would end up with pure metal A and a laminate structure.

EUTECTIC ALLOY.

Point E on the graph occurs at a certain critical ratio and is the lowest freezing/melting point that can be obtained. The material with this ratio is called a EUTECTIC ALLOY. The structure of the solid is entirely laminar and this might produce desirable properties in the alloy.

CASE 3 - Two Metals are Soluble Both in the Liquid and Solid State.

An example of this is nickel and copper that has similar size molecules and both form a FCC crystal lattice. The equilibrium diagram is shown below.



The melting points of pure nickel and copper are 1453°C and 1083°C respectively. Because they are soluble in both states, the diagram consists of only two lines, the solidus and liquidus. In between the substance is a pasty solution.

The molten alloy starts off as a uniform liquid. When cooled slowly to temperature T on the liquidus line we have a liquid of composition X and a solid of composition Y. Further cooling to temperature T₂ produces a liquid of composition X₂ and a solid of composition Y₂. In this condition the dendrites are forming with a uniform structure in a liquid of uniform structure. Cooling produces a liquid with less and less nickel and a solid with more and more copper. Finally the whole structure is solid at temperature T₃ and if equilibrium is reached due to diffusion, a uniform solid solution will form with a composition Y₃.