EDEXCEL NATIONAL CERTIFICATE

UNIT 10: PROPERTIES AND APPLICATIONS OF ENGINEERING MATERIALS

NQF LEVEL 3

OUTCOME 1 - TUTORIAL 1
THE STRUCTURE and PROPERTIES OF METALS

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 e.g. plain carbon steel, cast iron (grey, white, malleable, wrought iron), stainless and heat-resisting steels (austenitic, martensitic, ferritic); non-ferrous e.g. 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 eg 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

1. **INTRODUCTION**

2. **Introduction to Materials Classification and Terminology**
   Crystalline
   Amorphous

3. **Atomic Structures of Materials.**
   Atomic Structure
   Types of Bonds
   Crystal Lattices
   Carbon

4. **Structure of Metals**
   Ferrous
   Non Ferrous

5. **Heat Treatment**
   Ferrous
   Non Ferrous

1. INTRODUCTION

In engineering and technology the knowledge of materials has been at the forefront of science and has enabled us to produce amazing advances in all fields from medicines to electronics. We need to know about the mechanical properties (such as strength, durability, ductility and so on), the thermal properties (such as specific heat, melting point and conductivity), electrical properties (such as resistivity), magnetic properties, optical properties and many others.

This module is about materials used for manufacturing, in particular metals, plastics and ceramics. The more you understand the molecular structure of atoms, the more you will understand the nature of the material that can be made from them. The goal of this module is to enable you to select the best materials to manufacture a given item so that it performs the desired task and can be made as economically as possible.

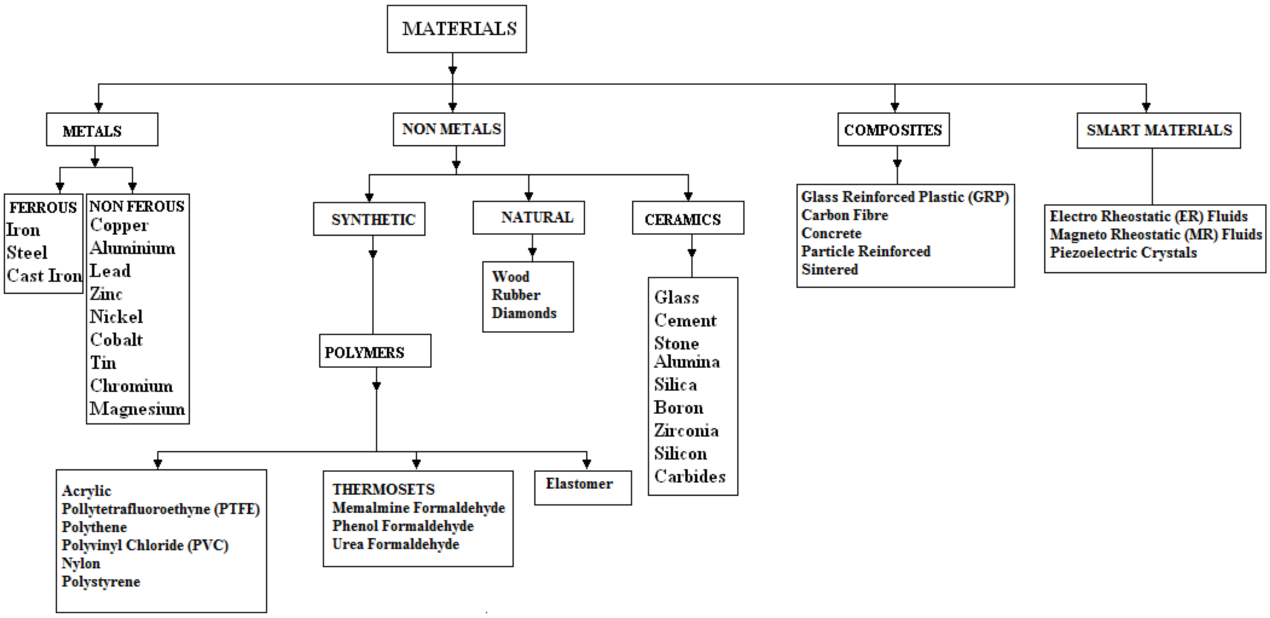
All materials are made up of atoms and combinations of atoms called molecules. The structure determines the engineering properties of the material. The following explanation about atomic structure is not comprehensive but beginners might think so. The subject is much more complex than described here and studying it will leave unanswered questions. There is a wealth of information on the internet and much of it appears contradictory. This is because explanations are often simplified to avoid going into too much detail. Hopefully the information here is sufficient to give you a good start on understanding engineering materials.

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.

2. INTRODUCTION TO MATERIAL CLASSIFICATION AND TERMINOLOGY

Engineering materials are classified in various ways depending on the properties of the materials you wish to highlight. The chart below shows the way they are classified in this tutorial and during the course of the tutorial you will learn what is special about them.



3. ATOMIC STRUCTURE OF MATERIALS

The way atoms join together to form a solid material can be in a strict pattern (crystalline) or just a uniform mixture (amorphous).

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, a crystalline structure will change into an amorphous liquid.

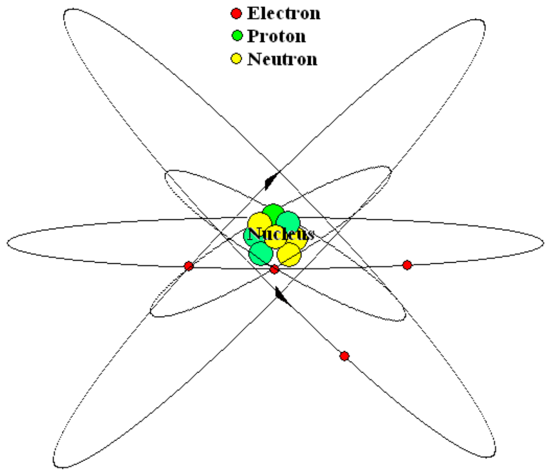
Materials may exist in a pure form or in some other form in a combination with other materials. How atoms and molecules stick together largely depend on its atomic structure and you should study this next.

ATOMS

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.

STRUCTURE OF THE ATOM

The simplest model for molecules and atoms is to represent them as small spheres. This is very simplistic and we know that an atom is much more complicated. The common model used to represent an atom is that of a **nucleus** orbited by small particles called **electrons**. The orbit is very large compared to the size of the nucleus. Electrons orbit the nucleus at various distances and form spherical shells.

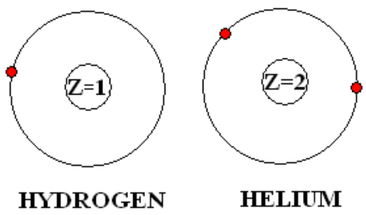


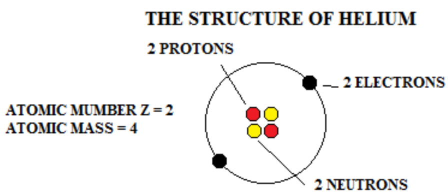
The nucleus is made up of two sub atomic particles called **protons** and **neutrons** that clump together. These are large compared to the electrons. The protons carry a positive charge of electricity. The electrons carry a negative charge of electricity (-1.6×10^{-19} Coulomb). The neutrons only affect the mass of the atom and have no electric charge.

Electrons have a negligible mass so the mass of an atom is the mass of the nucleus. Protons and neutrons have similar mass and size. The mass number is the total of both. In the lighter elements the number of protons and neutrons are the same but as the atomic number increases the number of neutrons increasingly exceeds the number of protons. The number of protons in an atom is the atomic number Z.

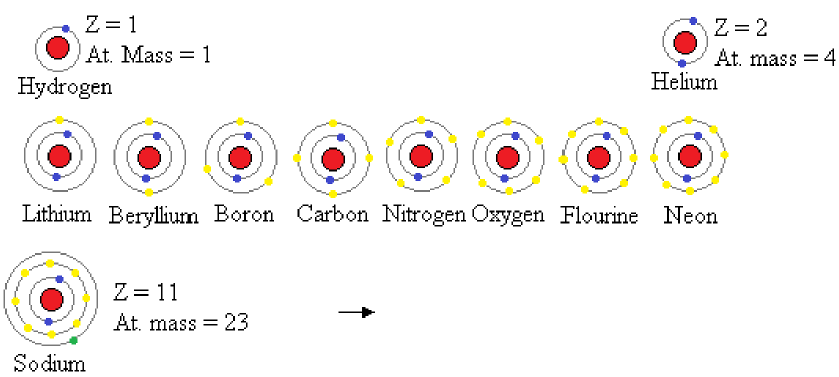
Positively and negatively charged particles are pulled together by a force of attraction and so the force between the electrons and protons keep the electrons in orbit. The total positive charge of the nucleus is always equal to the total negative charge of the electrons.

Electrons orbit the nucleus in shells of different sizes. There are a maximum number of electrons that can exist in a given shell. The first shell can contain a maximum of two electrons so if the nucleus has one proton (Z = 1) there is only one electron and we have the Hydrogen atom. If the nucleus has two protons (Z = 2), we must have two electrons and this gives us Helium.





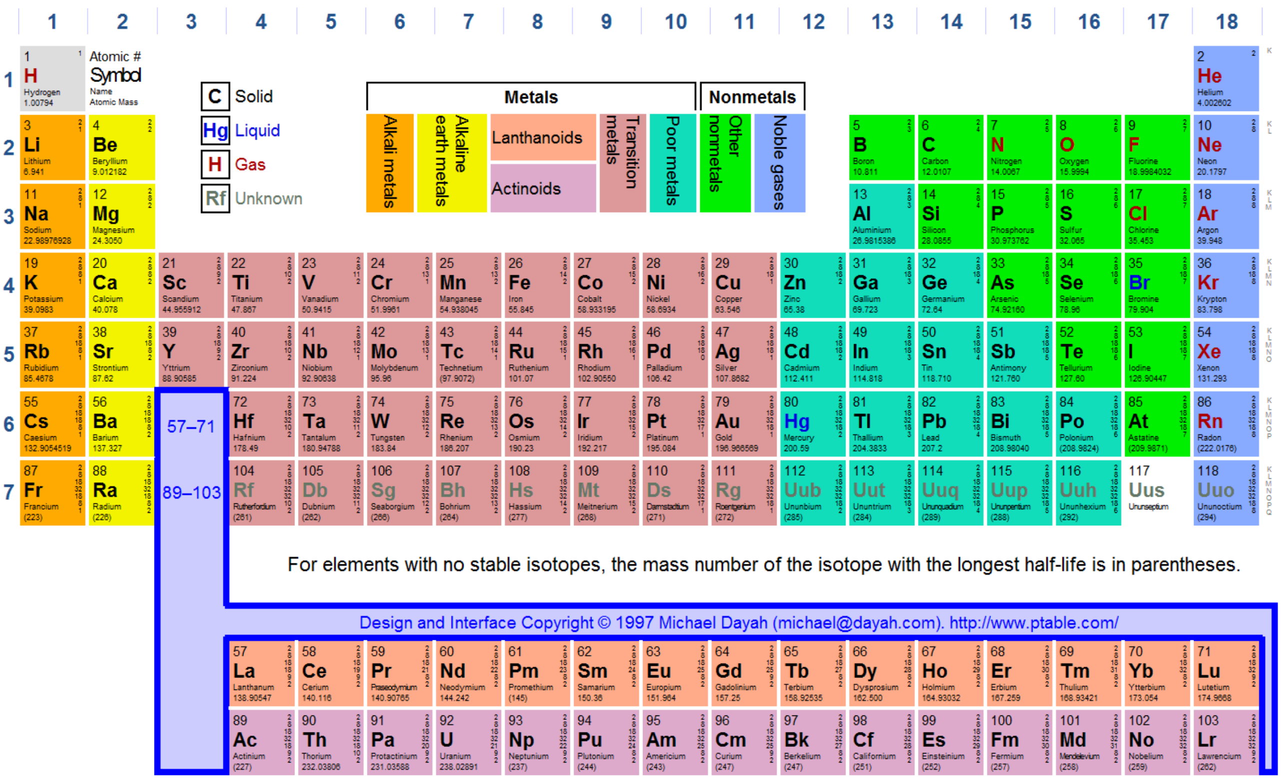
As the charge of the nucleus increases another shell is formed with anything from 1 to 8 electrons. After this another shell is formed with up to 18 electrons and so on. Each atom with equal numbers of electrons and protons is an element. The elements are arranged into a periodic table, part of which is shown next.



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. All elements with a complete outer shell are neutral and have no attraction to other atoms. All the rest have an incomplete outer shell called the valence shell and this makes them able to attract other atoms and form more complex molecules. Note that the number of neutrons sometimes differ from the number of protons (e.g. sodium 11 and 12 respectively) giving an atomic mass of 23 (actually 22.989). The rules governing the number of electrons are not covered here.

ISOTOPES

The number of protons in a stable element is shown in the periodic table. However there are many instances where the nucleus contains more or less neutrons than normal giving a slightly different atomic mass. For example carbon has 6 electrons so it should have 6 protons and 6 neutrons giving an atomic mass of 12. It is found that it can also exist with 7 or 8 neutrons giving atomic masses of 13 and 14. These are called isotopes. Naturally occurring materials may have various amounts of isotopes and the average molecular mass is usually given in the periodic table (e.g. 12.0107 for carbon).You can find many examples by exploring the periodic table at this link http://www.ptable.com/
It is interactive and gives other data as well.



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	TI	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	Actinum
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	Tn	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			

SELF ASSESSMENT EXERCISE No.1

1. How many electrons does a single copper atom have and how many in its outer shell?

2. What is the mean molecular mass of iron and how many protons are there in a single atom?

3. Conduct some research and find and write a definition of a metal.

4. Conduct some research and write a definition of a noble gas.

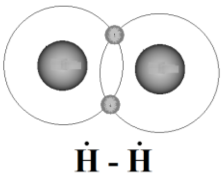
VALENCYand ATOMIC BONDS

It was stated above that atoms with incomplete outer shells are able to stick to other atoms. This is called bonding and it is largely electro-magnetic in nature. An atomic bond is the link that pulls them together. The topic is quite complicated and the following is grossly simplified. The outer shell of an element is called the valence shell and the electrons in this shell are the easiest to dislodge. The word valence or valence number refers to the number of bonds formed by an atom of a given element. The valence of an element depends on the number of valence electrons that may be involved in the forming of valence bonds. An element with one bond is called univalent and one with two bonds is called divalent but the subject is much more complex than this simple definition indicates.

There are several ways that bonds are formed between atoms the main ones are ***covalent, ionic*** and ***metallic***.

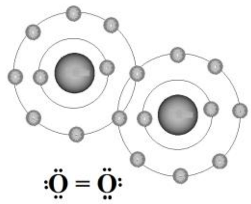
COVALENT BOND

Covalent bonds consist of the sharing of one or more pairs of electrons by atoms. Atoms with a complete outer shell are stable and can exist on their own. Atoms with an incomplete outer shell will join to other atoms with an incomplete shell.

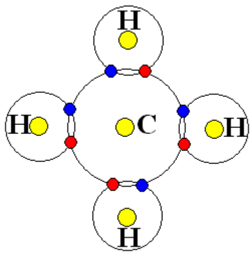


For example, ***hydrogen*** has an incomplete outer shell and will attract another hydrogen atom to form a molecule consisting of two atoms that share a common electron in order to complete the outer shell of both and becomes neutral. This molecule has a symbol H_2 to indicate there are two atoms. Note the short hand way of showing hydrogen with one electron and one bond.

Helium, on the other hand, is neutral because it has a complete outer shell and will happily exist as one atom (He). Oxygen and Nitrogen have incomplete shells and normally exists as O_2 and N_2 and so on.



Consider the example of the ***oxygen*** molecule. The oxygen atom has an incomplete outer shell with 6 electrons. 8 are needed to complete the shell so they bond together by sharing 2. Note the shorthand way of showing oxygen with 6 electrons and two bonds.



Consider the example of Methane CH_4. The molecule is formed as shown. The carbon atom has four electrons in the outer shell but would be more stable with eight. The hydrogen atom has one electron but would be more stable with two. If each hydrogen atom shares its electron with the carbon both are stable.

You will find more information at these web sites
http://en.wikipedia.org/wiki/covalent_bond
http://www.accessexcellence.org/RC/VL/GG/cov_IonicBs.html
http://www.visionlearning.com/library/module_viewer.php?mid=55

ELECTROVALENT OR IONIC BONDING.

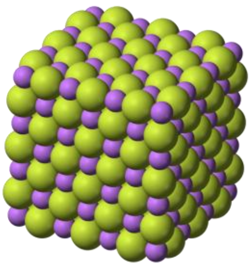
IONS

Normally the number of electrons orbiting a nucleus is equal to the number of protons producing equal and opposite charges. For any two elements, the difference in the number of electrons is the same as the difference in the number of protons so no electrostatic force exists between them. However, atoms can gain or lose electrons upsetting this balance. When this happens they are called ***IONS*** and these attract each other to form an ionic bond.

Ions are usually formed by metals with an incomplete outer shell losing electrons and non metals with an incomplete outer shell gaining electrons so that both achieve a full outer shell. To fully understand this you would need to study the energy changes that occur to see that this produces a more stable arrangement. When it happens the nucleus is no longer balanced with the electrons and the ions become electrostatically charged. The atom that gains electrons becomes negatively charged (negative ion or cation) and the atom that gives up electrons becomes positively charged (positive ion or anion). Remember that electrons carry a negative charge. Ions attract each other like a pair of magnets and bond together. This is called **electrovalent** or **ionic** bonding.

An example is common salt (Sodium Chloride) NaCl. The sodium is metallic and the chlorine is non metallic. Sodium normally has 11 electrons and 11 protons. Chlorine normally has 17 electrons and 17 protons. When sodium gives up an electron to the chlorine, both obtain complete outer shells. The sodium having one more proton than electrons has a charge of 1 and the chlorine having one more electron than protons has a charge of -1. We show the ions as Na+ Cl-

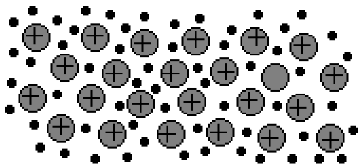
Another example is Lithium (metal) and Fluorine (non metal). If the lithium gives up one electron to the fluorine both obtain a full outer shell. The lithium has a charge of +1 and the fluoride -1.



For each case such as this, the two elements join 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.

METALLIC BOND.

The electrons in the outer shell are the easiest to detach and the more shells there are the more electrons there are in the outer shell. Sometimes the electrons are so easy to detach that they cannot be associated with one atom and they wander around between atoms. This happens with metals and gives us metallic bonding. The nucleus is held in position by a swarm of electrons acting like glue between them. 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.



SELF ASSESSMENT EXERCISE No.2

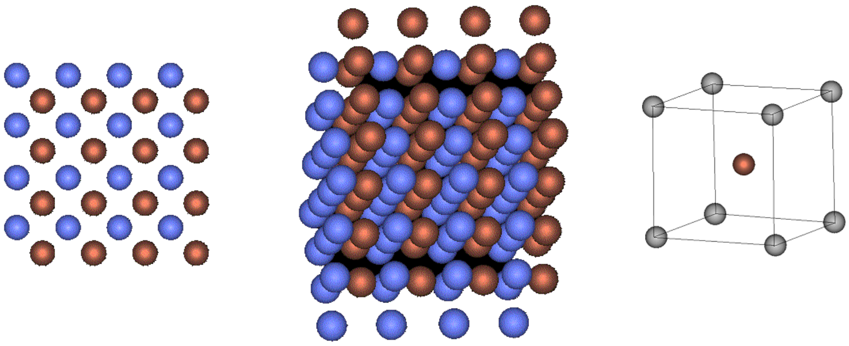
1. All chemical compounds ending in “ide” such as sodium chloride are called salts. Define a salt and state what kind of bond exists between the elements of a salt.

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 (alpha) iron and γ (gamma) iron.

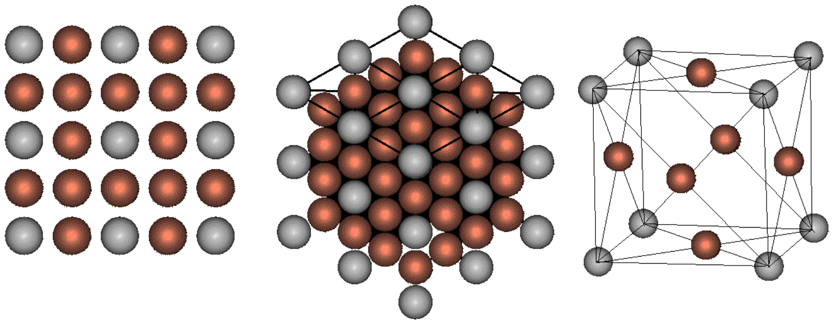
BODY CENTRE CUBIC (BCC)

The atoms stack themselves in layers as shown so that each is at the centre of a cube. A single cube has one atom 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.



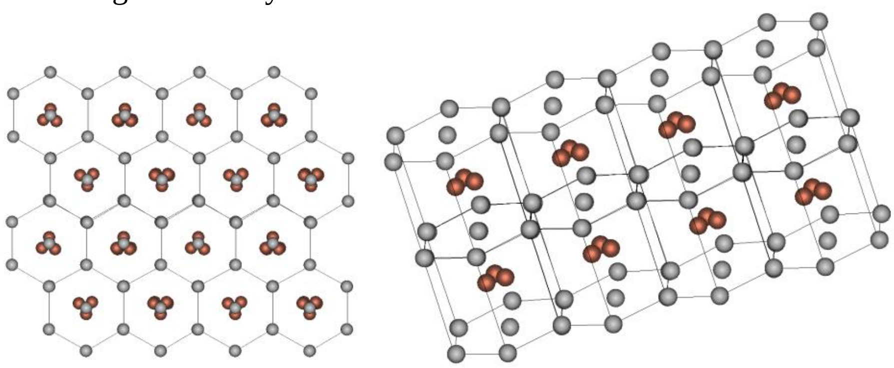
FACE CENTRE CUBIC (FCC)

The atoms arrange themselves in alternate square shaped layers. One layer has five atoms with one at each corner and one at the centre. The next layer has 4 atoms mid point between the corners. The result is a set of cubes with an atom at each corner and one in the middle of each face. This is the structure of γ iron, aluminium, copper, gold and nickel.

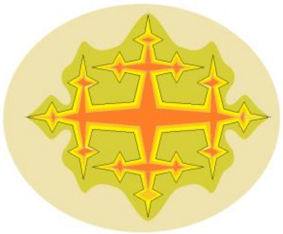


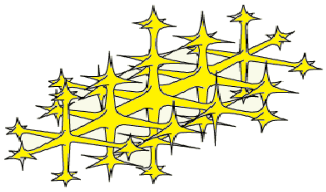
HEXAGONAL CLOSED PACK (HCP)

Visualise the structure as an extruded hexagon with an atom at every corner plus three packed into the middle as shown and one in the centre of each end face. 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.



When crystals form as a result of solidification, they start from a seed point and spread out in a way that has maximum surface area. The shape formed is called DENDRITE. 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.





SELF ASSESSMENT EXERCISE No.3

1. What is the most likely crystal lattice for salt?

2. What is the crystal lattice for Alpha (α) Iron and Gamma (γ) iron?

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

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

4. THE STRUCTURE OF METALS

Metals are of great importance in engineering because they possess so many properties (such as conductivity and ductility) that are needed to make components and structures. 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.

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.

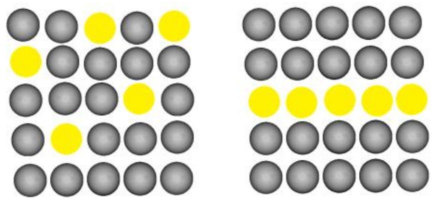
The amount of substance that can be dissolved before it becomes saturated depends upon the temperature. If we warm the water, we can dissolve more salt. If we cool a saturated solution, crystals will form of the dissolved substance. Interestingly, if we freeze salty water, on solidification, the salt 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.

SUBSTITUTIONAL SOLID SOLUTIONS

An alloy of two metals can be formed when the atoms of one (the solute) replaces some of the atoms of the bulk metal (the solvent). This takes place within the crystal lattice and the process is called substitutional and it forms a substitutional solid solution. This is most likely when the atoms of both form a similar crystal structure and have a similar size. For example, copper atoms may substitute for nickel atoms without disturbing the F.C.C. structure of the nickel crystals. The process may be disordered or ordered. This is illustrated below.



Disordered Ordered

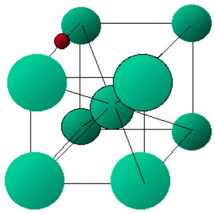
INTERSTICIAL COMPOUND

It might be useful to define a compound. A compound is a molecule made up from at least 2 different types of atoms bonded together. Do not confuse the following with solid solutions in which the atoms do not form a bond. A number of metals combine together to form an intermediate phase or intermediate compound known as intermetallic.

This forms when one of the molecules is so small that it fits into the spaces (interstices) between the larger molecules (called the interstitial spaces).

Iron Carbide (Fe_3C) or cementite is an example. Cementite is an interstitial compound containing 3 iron atoms for every 1 atom of Carbon. The molecule contains iron and carbon bonded together.

Carbon atom (in red) fitting in between the larger iron atoms thus forming a lattice structure which will form the intermetallic compound Cementite.



ELECTRON COMPOUNDS

These have a crystal structure different to the crystal structure of the separate elements and the separate elements have different valence so that one is electro- positive and the other is electro – negative. An example of an electron compound would be an alloy of the elements Magnesium and Tin which combine to form an intermetallic compound Mg_2Sn. The composition of the compound is fixed and consists of two atoms of Magnesium combining with one atom of Tin. Metallic compounds form a crystal lattice with the atoms of the alloying metals taking up specific positions within the lattice. These compounds are usually hard and brittle.

SELF ASSESSMENT EXERCISE No.4

1. Research the internet and name a few substances that form as an interstitial, substitutional and electron compound.

FERROUS MATERIALS

Ferrous metals are alloys or compounds in which most of the atoms are iron. 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 is 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 the slides on machine tools are often machined from cast iron.

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.

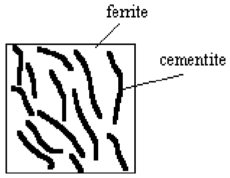
CARBON STEELS

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

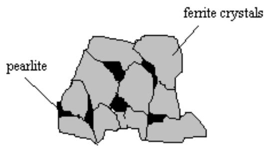
STRUCTURE OF CARBON STEEL

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 STRUCTURE OF PEARLITE

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.



THE STRUCTURE OF MEDIUM CARBON STEEL

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.

THE STRUCTURE OF HIGH CARBON STEEL

Carbon steel can have a wide range of mechanical properties (e.g. strength, hardness, toughness, and ductility) and these properties can be changed by heat treatment. Heat treatment changes the structure of the carbon and steel and this is a large area of study.

SELF ASSESSMENT EXERCISE No.5

1. State 3 advantages and one disadvantage of making something from cast iron. Name some items that are made from cast iron.
2. If a component could perform equally well whether it is made from mild steel or titanium, for what simple reason would steel be chosen?
3. What % carbon does steel contain when its structure is entirely pearlite?
4. What is the main mechanical property of cementite?
5. Conduct further research and then sketch and describe the crystal structure of cementite. Here are two useful websites.
   http://www.msm.cam.ac.uk/phase-trans/2003/Lattices/cementite.html)
   http://www.ul.ie/~walshem/fyp/sub%20menu%20iron%20carbon.htm

ALLOY STEELS

Besides carbon, iron is alloyed with other elements to produce desirable properties. Generally they fall into two groups: **low alloy steels** and **high alloy steels** depending on the % of alloying elements. This is done in order to improve the mechanical properties. Commonly alloy elements include manganese (the most-common one), nickel, chromium, molybdenum, vanadium, silicon and boron. Less common elements include aluminium, cobalt, copper, cerium, niobium, titanium, tungsten, tin and zirconium. Some of these find uses in exotic and highly-demanding applications, such as in the turbine blades of jet engines, in spacecraft and in nuclear reactors. Because of the ferromagnetic properties of iron, some steel alloys find important applications where magnetism is important including electric motors and transformers. This is a vast area of study and cannot possibly be covered here.

Element	Percentage	Primary function
Aluminium	0.95–1.30	Alloying element in nitriding steels
Bismuth	-	Improves machinability (makes it easier to cut on machine tools)
Boron	0.001–0.003	A powerful hardenability agent
Chromium	0.5–2	Increases hardenability
	4–18	Used in stainless steel and increases corrosion resistance
Copper	0.1–0.4	This can help improve corrosion resistance
Lead	-	Often with sulphur makes the steel machinable at high speeds (free cutting)
Manganese	0.25–0.40	Combines with sulphur with phosphorus to reduce the brittleness. Also helps to remove excess oxygen from molten steel.
	>1	Increases hardenability by lowering transformation points and causing transformations to be sluggish
Molybdenum	0.2–5	Stable carbides inhibit grain growth. Increases the toughness of steel, thus making molybdenum a very valuable alloy metal for making the cutting parts of machine tools and also the turbine blades of jet engines. Also used in rocket motors.
Nickel	2–5	Toughens the steel
	12–20	Increases corrosion resistance
Silicon	0.2–0.7	Increases strength
	2.0	Spring steels
	Higher percentages	Improves magnetic properties
Titanium	-	Fixes carbon in inert particles; reduces martensitic hardness in chromium steels
Tungsten	-	Also increases the melting point.
Vanadium	0.15	Stable carbides; increases strength while retaining ductility; promotes fine grain structure. Increases the toughness at high temperatures

SELF ASSESSMENT EXERCISE No.6

Conduct some research on the internet to answer the following. In each case describe the properties of the steel that make them suitable for purpose and manufacture.

1. The kind of steel used to make modern railway track.
2. The kind of steel is used to make car panels and the properties of the steel that makes it suitable.
3. The kind of alloying elements used in the manufacture of high quality hack saw blades.
4. The kind of steel that can be made into cheap wire for garden fences.
5. The kind of steel used to make crank shafts in internal combustion engines.
6. The kind of steel used to make connecting rods in internal combustion engines.
7. The ferrous material commonly used to make engine blocks.

STAINLESS STEEL

One important alloy steel group is ***Stainless Steel.*** The name covers a wide range of steel types and grades for corrosion or oxidation resistant applications. 'Stainless' is a term coined early in the development of these steels for cutlery applications. It was adopted as a generic name for these steels and now 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 such as formability, strength and cryogenic toughness. These include metals such as:

- Nickel
- Molybdenum
- Titanium
- Copper
-

Non-metal additions are also made, the main ones being:

- Carbon
- Nitrogen

Stainless steels of various kinds are used in thousands of applications such as :-

Domestic Applications: - cutlery, sinks, saucepans, washing machine drums, microwave oven liners and razor blades.

Construction:- cladding, handrails, door and window fittings, street furniture, structural sections, reinforcement bar, lighting columns, lintels and masonry supports.

Transport: - exhaust systems, car trim/grilles, road tankers, ship containers, ships chemical tankers and refuse vehicles.

Chemical/Pharmaceutical:-pressure vessels and process piping.

Oil and Gas: - platform accommodation, cable trays, and sub-sea pipelines.

Medical: - Surgical instruments, surgical implants and MRI scanners.

Food and Drink: - Catering equipment, brewing, distilling and food processing.

Water: - Water and sewage treatment, water tubing and hot water tanks.

General: - springs, fasteners (bolts, nuts and washers) and wire.

This a useful link to find out more about stainless steel. http://www.bssa.org.uk/index.php

SELF ASSESSMENT EXERCISE No.7

1. Why is stainless steel used for containers where cleanliness and a sterile environment is required?

2. An architect is trying to decide whether a balcony safety rail and supports should be made from cast iron or stainless steel. What are the advantages and disadvantages of both materials?

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..

TITANIUM
- low-density element (approximately 60% of the density of iron)
- can be highly strengthened by alloying and working.
- nonmagnetic
- good heat-transfer properties.
- coefficient of thermal expansion lower than that of steels and less than half that of aluminium.
- high melting point (higher than steel).
- immune to attack by most mineral acids and chlorides
- non-toxic and very compatible with human tissue.

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 OF NON FERROUS METALS

Some of the alloys formed by non ferrous metals are:
Brass – Brass is basically a substitutional alloy of zinc in copper. It has a range of properties depending on the exact structure including strength, machinability, ductility, wear-resistance, hardness, colour, antimicrobial, electrical and thermal conductivity, and corrosion-resistance.
Brass is used in instruments (musical and other), coins, fixtures such as doorknobs, bolts, etc. Brass is also used to decorate many household items such as clocks and mirrors.
Bronze – Is an alloy of copper with up to 10% that may contain phosphor, silicon, manganese, aluminium, lead, iron and other elements. It can be quite hard and brittle. The tin gives the material resistance to wear and it is often better than brass in resisting corrosion.
The various types of bronze have different levels of wearability, machinability, corrosion-resistance and ductility for deep drawing. Bronze parts are typically used for bearings, clips, electrical connectors and springs.
Aluminium bronze is a copper-aluminium alloy that may contain iron, nickel, and/or silicon for greater strength. It is used for tools and, because it will not spark when struck, for parts to be used around flammable materials. Aluminium bronze is frequently used for aircraft and automobile engine parts.
Manganese bronze is often used for ship propellers because it is strong and resists saltwater corrosion.
Aluminium- can be made strong by adding other elements and on a weight for weight basis is stronger than steel. These alloys are often classed as wrought or cast. Wrought alloys can be rolled into plates. Aluminium alloys are extensively used in the production of automotive engine parts, transport, packaging, electrical application, medicine, and construction of homes and furniture. High grade alloys are widely used in the aeronautical industry because of the lightness and strength. They are widely used to make tubes for structures requiring the same properties.
One of the best known alloys is **Duralumin** containing up of 90% aluminium, 4% copper, 0.5%-1% magnesium, and less than 1% manganese.
Titanium- Pure titanium is suited to many uses including use in surgery to support bones and teeth. The alloys have up to 6% aluminium and 4% vanadium by weight. This mixture forms a solid solution which varies with temperature and so allows it to be strengthened by heat treatment.
The combination of high strength, stiffness, toughness, lightness, and resistance to corrosion over a wide range of temperatures makes it highly suited for aerospace structures. The excellent corrosion resistance and biocompatibility makes it useful in chemical and petrochemical applications and salt water applications.

SELF ASSESSMENT EXERCISE No. 8

1. Copper is a good conductor of electricity and heat. What mechanical properties make it suitable for forming into wires and tubes?

2. The leading edges of supersonic aeroplanes are often made from titanium alloy. What are the properties that make it suitable for this?

3. Titanium alloy is better than steel for most applications. Why is it not more widely used in engineering?

4. What are the mechanical properties of aluminium that makes it suitable for the manufacture of drink cans and foil wrapping?

5. Decorative frames for pictures and fire places are often made from brass or brass plated steel. What is the property of brass that makes it so suitable?

5. HEAT TREATMENT

The mechanical properties of materials can be changed by heat treatment. Let's first examine how this applies to carbon steels.

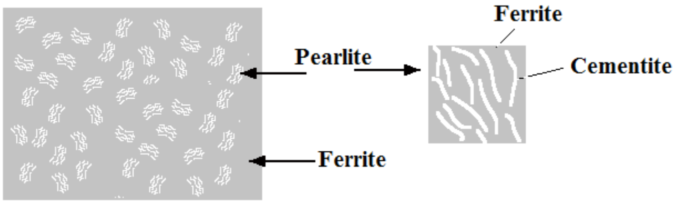
CARBON STEELS

In order to understand how carbon steels are heat treated we need to re-examine the structure. Steels with carbon fall between the extremes of pure iron and cast iron and are classified as follows.

NAME	CARBON %	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

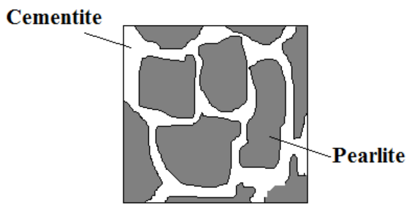
STRUCTURE

Carbon and iron form complex crystals on solidification. Crystals of ***IRON CARBIDE***, Fe_3C, (also called ***CEMENTITE)*** forms up to a maximum of 13% of the weight. This is embedded in pure iron to form a microstructure called ***PEARLITE***. At the same time crystals of pure iron form producing the structure shown.



STRUCTURE OF LOW/MEDIUM CARBON % STEEL

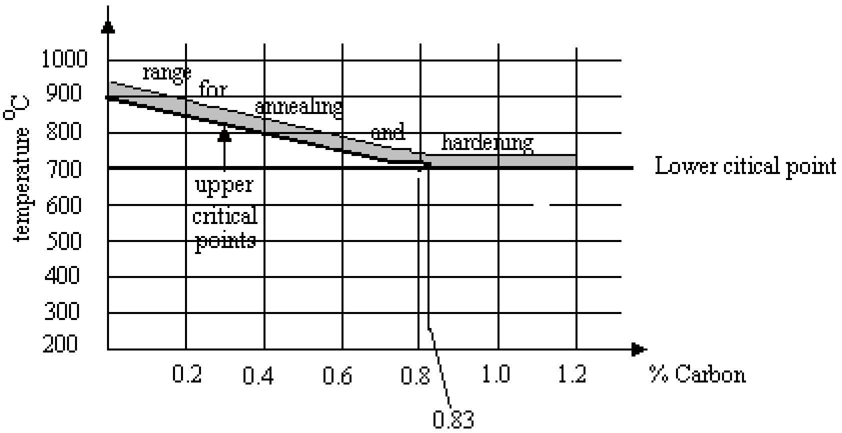
If the carbon is increased beyond 0.83% all the ferrite around the pearlite is used up forming pearlite and the structure becomes pearlite surrounded by cementite as shown.



STRUCTURE OF HIGH CARBON STEEL %

HEAT TREATMENT of CARBON STEELS

Steels containing carbon can have their properties (hardness, strength, toughness etc) changed by heat treatment. Basically if it is heated up to red hot and then cooled very rapidly the steel becomes harder. Dead mild steel is not much affected by this but a medium or high carbon steel is.



When the steel is heated up to 700°C the carbon starts to dissolve into the ferrite to form a uniform structure called ***AUSTENITE***. Austenite has a face-centred cubic crystal of ferrite and carbon. As the temperature increases, the process continues until at some higher temperature the structure is all austenite. The temperatures at which this process starts and ends are called the lower and higher critical points. The upper critical point changes with %C as shown on the diagram. Notice that above 0.83%C the upper and lower points are the same. If the steel is cooled slowly, the reverse process occurs and cementite and pearlite forms. The following are all forms of heat treatment.

HARDENING

If steel just hotter than the upper critical point is plunged into oil or water (quenching) the steel cools very quickly. Instead of pearlite forming, a structure known as ***MARTENSITE*** is formed. This is a very hard substance and the resulting steel is hard. The degree of hardness depends on how fast it is cooled and water quenching is quicker than oil quenching. The graph shows the critical temperature plotted against %C. For example 0.3 % carbon steel should be heated to a temperature between 880 and 910^oC.

TABLE OF HARDNESS OF QUENCHED STEELS

Carbon %	0.1	0.3	0.5	0.7	0.9	1.2
Brinell Hardness	150	450	650	700	680	690

ANNEALING

The purpose of annealing is to soften hard steel. The steel is heated slowly to the upper critical point and held at this temperature for a time. It is then allowed to cool slowly. This process removes any stresses trapped in the material due to quenching, machining or mechanical working (such as rolling it).

TABLE OF ANNEALING TEMPERATURES RANGES FOR CARBON STEELS

Carbon %	0.12	0.12/0.25	0.3/0.5	0.5/0.9	0.9/1.3
Temperature ^oC	875/925	840/970	815/840	780/810	760/780

NORMALISING

This is similar to annealing. When the steel has been kept hot for a long time (e.g. for forging), the crystals become very large. When a cold steel has been mechanically worked, say by cold drawing it into a bar, the crystals are elongated in one direction. Normalising returns the crystal structure to normal and it is carried out by cooling the steel in air.

TEMPERING

The crystalline structure of Martensite is Body Centred Tetragonal (BCT). Martensite is easily converted into Austenite (a Faced Centre Cubic crystal FCC) by heating. It is easier to quench steel and produce an abundance of Martensite and then produce the required hardness by heating to temperatures below the lower critical point. This allows some of the Martensite to change into Pearlite. This softens the steel but also makes it tougher.

TABLE OF TYPICAL TEMPERING TEMPERATURES

Component	Turning Tools	Drills Milling	Punches Twist Drill	Cold Chisels	Springs
Temperature ^oC	230	240	260	280	300

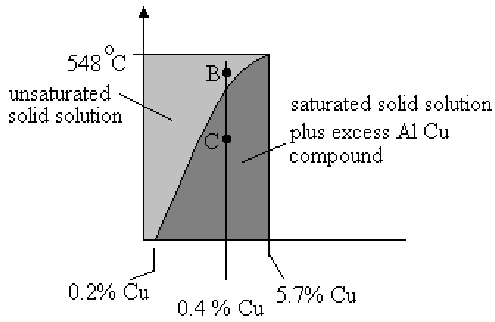
HEAT TREATMENT OF OTHER METALS

Some metals such as aluminium alloys are classed as heat treatable or non heat treatable. The heat treatment methods for other metals and alloys are numerous and would need a vast amount of study to cover them all. One important method worth studying is solution heat treatment and aging.

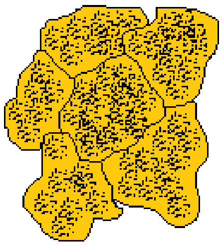
SOLUTION HEAT TREATMENT AND AGING

This is a process in which an alloy is heated to a suitable temperature and held at that temperature until one element has dissolved as much as possible into the other (solid solution). It is then cooled rapidly to hold that constituent in solution. Most solution heat treatments soften or anneal

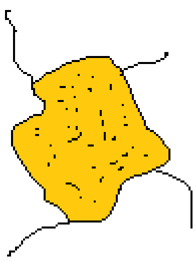
Consider the case of an aluminium-copper alloy. Part of the thermal equilibrium diagram is shown. This shows that in going from 0 to 548°C the amount of copper that can be dissolved in aluminium increases from 0.2% to 5.7%. The light grey section contains an unsaturated solid solution. The dark grey portion contains the maximum dissolved copper possible (saturated solution) and any more copper than these forms the compound $CuAl_2$.



Consider the alloy known as Duralumin widely used in making skins for aircraft and containers. This alloy contains 4% copper. Suppose the molten solution cools down very slowly. First it will pass through the unsaturated portion and will eventually end up as a saturated solution with excess copper.



At room temperature the structure will be as shown left with a background of solid saturated solution with 0.2% Cu and the rest are particles of compound containing the other 3.8% of the copper. The compound is a hard and brittle substance so duralumin in this form is brittle.



Suppose we know heat up the alloy to point C. The compound gradually dissolves into the solid solution (diffusion of atoms) as shown. At point B, just below the melting temperature, all the copper is dissolved into the solid solution with no compound at all. The alloy has to be kept at this temperature long enough for the transformation to be complete. If the alloy is now quenched in water for rapid cooling, the copper is trapped in the solid solution and the solid solution is supersaturated. The quenched structure is stronger and more ductile. This is an example of ***SOLUTION TREATMENT***.

If the quenched duralumin is left at room temperature for a few days, the structure partially reverts to the equilibrium condition and the strength and hardness increases and the ductility reduces. This is called ***AGE HARDENING***. This process may be accelerated by heating the alloy to 160°C and this is called ***PRECIPITATION HARDENING***.

SELF ASSESSMENT EXERCISE No. 9

1. Describe the method of carburising.

2. What process would you use to harden:
   a) gear teeth?
   b) machine tool slideway?

3. Describe the process of full annealing.

4. Why can't wrought iron be heat treated or hardened?

5. Why can't cast iron be annealed?

6. Look up and list alloys that can be solution treated.