

Engineering Materials

1

Introduction to Eng. Materials :

Since the earliest days of the evolution of mankind , the main distinguishing features between human beings and other mammals has been the ability to use and develop materials to satisfy our human requirements. Nowadays we use many types of materials, fashioned in many different ways, to satisfy our requirements for housing, heating, furniture, clothes, transportation, entertainment, medical care, defense and all the other trappings of a modern, civilised society.

Most materials doesn't exist in its pure shape , it is always exist as a ores . During the present century the scope of metallurgical science has expanded enormously , so that the subject can now be studied under the following headings :

- a) Physical metallurgy
- b) Extraction metallurgy
- c) Process metallurgy

In the recent years studying the metallurgy science gave to humanity an ever growing range of useful alloys. Whilst many of these alloys are put to purposes of destruction, we must not forget that others have contributed to the material progress of mankind and to his domestic comfort.

This understanding of the materials resources and nature enable the engineers to select the most appropriate materials and to use them with greatest efficiency in minimum quantities whilst causing minimum pollution in their extraction, refinement and manufacture.

Selection of materials :

Let's now start by looking at the basic requirements for selecting materials that are suitable for a particular application. For example figure 1 shows a connector joining electric cables. The plastic casing has been partly cut away to show the metal connector. Plastic is used for the outer casing because it is a good electrical insulator and prevents electric shock if a person touches it. It also prevents the conductors touching each other and causing a short circuit. As well as being a good insulator the plastic is cheap, tough, and easily moulded to shape. It has been selected for the casing because of these properties – that is, the properties of

toughness, good electrical insulation, and ease of moulding to shape. It is also a relatively low cost material that is readily available.

The metal joining piece and its clamping screws are made from brass. This metal has been chosen because of its special properties. These properties are good electrical conductivity, ease of extruding to shape, ease of machining (cutting to length, drilling and tapping the screw threads), adequate strength and corrosion resistance. The precious metal silver is an even better conductor, but it would be far too expensive for this application and it would also be too weak and soft.

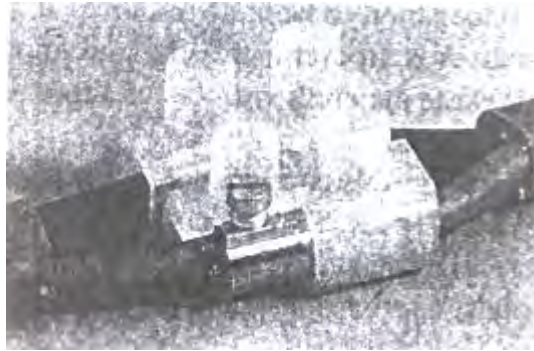


Figure 1. The electrical connector.

Another example as in figure 2 shows the connecting rod of a motor car engine. This is made from a special steel alloy. This alloy has been chosen because it combines the properties of strength and toughness with the ability to be readily forged to shape and finished by machining.



Figure 2. The connecting rod of motor car engine.

Thus the reasons for selecting the materials in the above examples can be summarized as :

❖ **Commercial factors** such as:

Cost, availability, ease of manufacture.

❖ **Engineering properties of materials** such as:

Electrical conductivity, strength, toughness, ease of forming by extrusion, forging and casting, machinability and corrosion resistance.

Engineering materials:

Almost every substance known to man has found its way into the engineering workshop at some time or other. The most convenient way to study the properties and uses of engineering materials is to classify them into 'families' as shown in figure below:

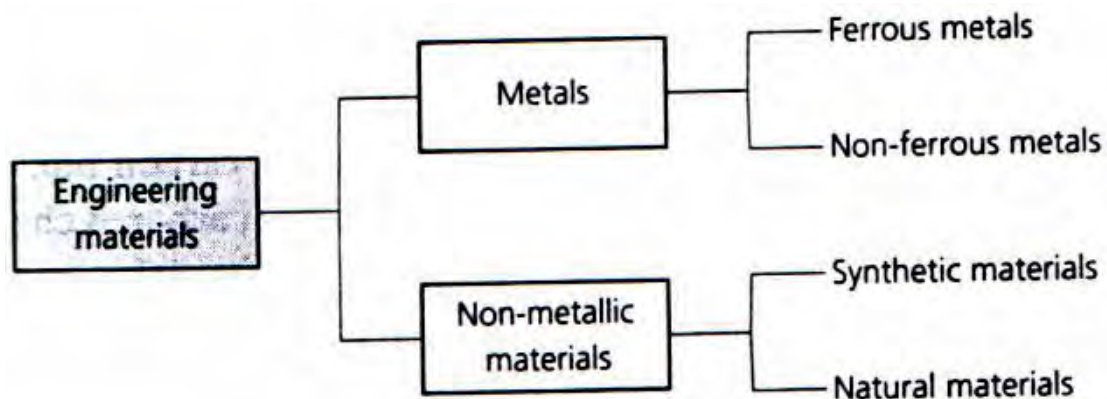


Figure 3. classification of engineering materials.

1. Metals

1.1 Ferrous metals

- These are metals and alloys containing a high proportion of the element iron.
- They are the strongest materials available and are used for applications where high strength is required at relatively low cost and where weight is not of primary importance.
- As an example of ferrous metals such as : bridge building, the structure of large buildings, railway lines, locomotives and rolling stock and the bodies and highly stressed engine parts of road vehicles.
- The ferrous metals themselves can also be classified into "families", and these are shown in figure 4.

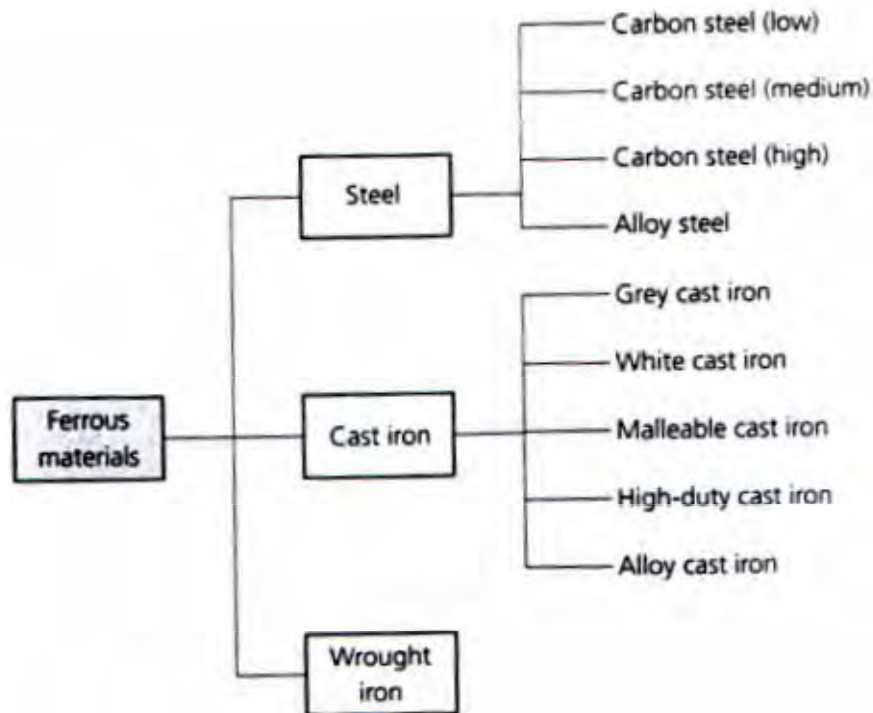


Figure 4. Classification of ferrous metals.

1.2 Non – ferrous metals

- These materials refer to the remaining metals known to mankind.
- The pure metals are rarely used as structural materials as they lack mechanical strength.
- They are used where their special properties such as corrosion resistance, electrical conductivity and thermal conductivity are required. Copper and aluminum are used as electrical conductors and, together with sheet zinc and sheet lead, are use as roofing materials.
- They are mainly used with other metals to improve their strength.
- Some widely used non-ferrous metals and alloys are classified as shown in figure 5.

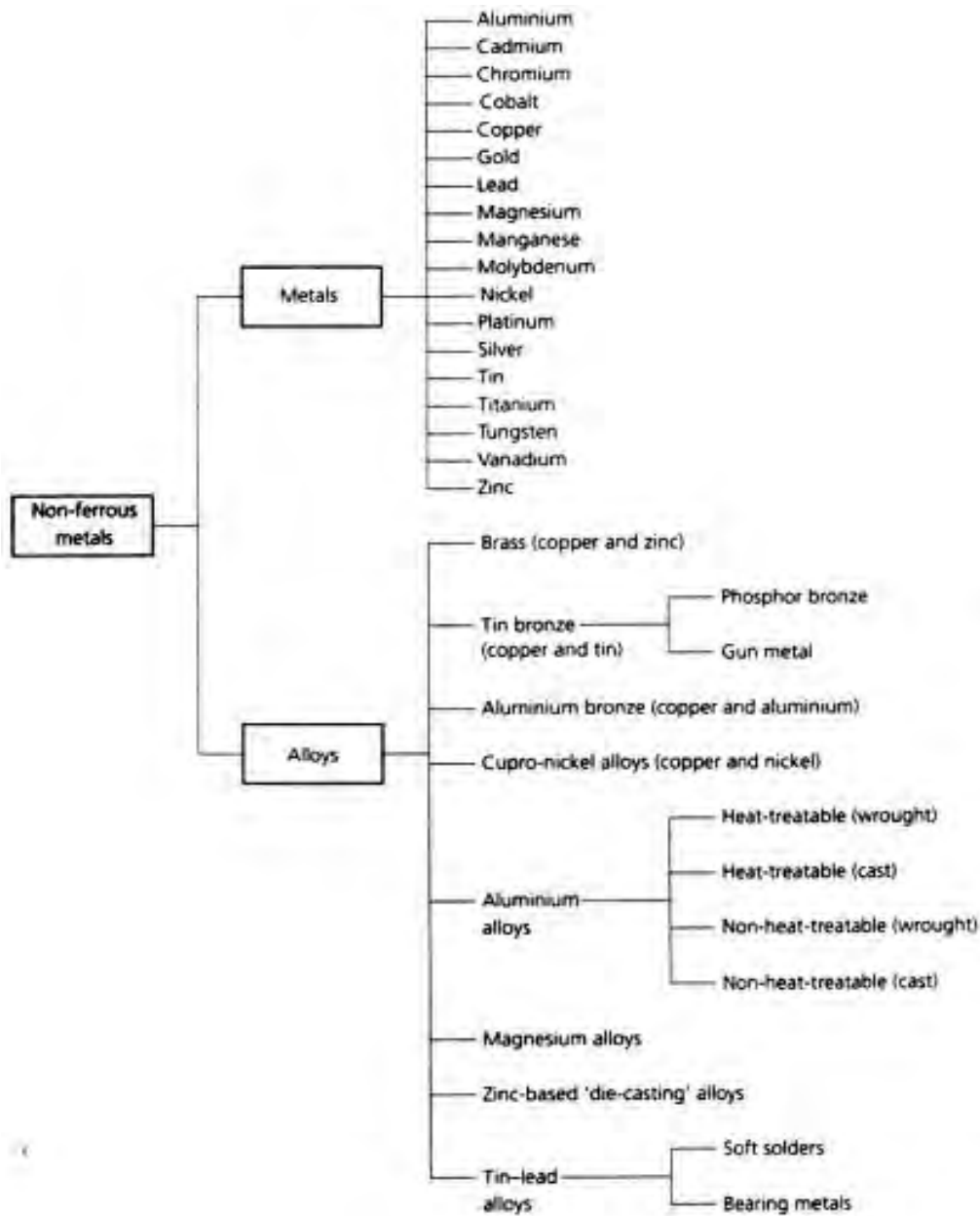


Figure 5. Classification of non-ferrous metals and alloys.

2. Non – metallic materials

2.1 Non – metallic (synthetic materials)

These are non – metallic materials that do not exist in nature, although they are manufactured from natural substances such as oil, coal and clay. Some typical examples are classified as shown in figure 6.

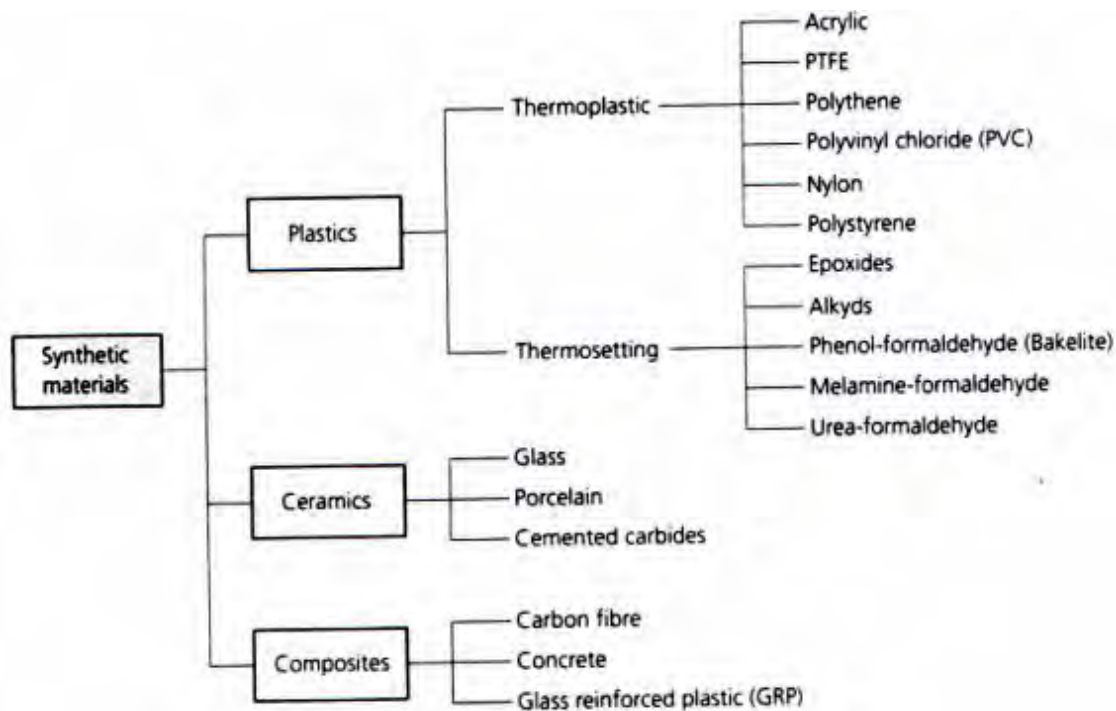


Figure 6. classification of synthetic materials.

- They combine good corrosion resistance with ease of manufacture by moulding to shape and relatively low cost.
- Synthetic adhesives are also being used for the joining of metallic components even in highly stressed applications.

2.2 Non – metallic (Natural materials)

Such materials are so diverse that only a few can be listed here to give a basic introduction to some typical applications.

- Wood: This is naturally occurring fibrous composite material used for the manufacture of casting patterns.
- Rubber :This is used for hydraulic and compressed air hoses and oil seals. Naturally occurring latex is too soft for most engineering uses but it is used widely for vehicle tyres when it is compounded with carbon black.
- Glass : This is a hardwearing, abrasion-resistant material with excellent weathering properties. It is used for electrical insulators, laboratory equipment, optical components in measuring instruments etaad, in the form of fibers, is used to reinforce plastics. It is made by melting together the naturally occurring materials : silica (sand), limestone (calcium carbonate) and soda (sodium carbonate).

- Emery : This is a widely used abrasive and is a naturally occurring aluminum oxide. Nowadays it is produced synthetically to maintain uniform quality and performance.
- Ceramic: These are produced by baking naturally occurring clays at high temperatures after moulding to shape. They are used for high – voltage insulators and high – temperature – resistant cutting tool tips.
- Diamonds: These can be used for cutting tools for operation at high speeds for metal finishing where surface finish is greater importance. For example, internal combustion engine pistons and bearings. They are also used for dressing grinding wheels.
- Oils : Used as bearing lubricants, cutting fluids and fuels.
- Silicon : This is used as an alloying element and also for the manufacture of semiconductor devices.

These and other natural, non-metallic materials can be classified as shown in figure 7.

Composite materials (composites)

These are materials made up from, or composed of, a combination of different materials to take overall advantage of their different properties.

In man-made composites, the advantages of deliberately combining materials in order to obtain improved or modified properties was understood by ancient civilizations. An example of this was the reinforcement of air-dried bricks by mixing the clay with straw. This helped to reduce cracking caused by shrinkage stresses as the clay dried out. In more recent times, horse hair was used to reinforce the plaster used on the walls and ceiling of buildings. Again this was to reduce the onset of drying cracks.

Nowadays, especially with the growth of the plastics industry and the development of high-strength fibers, a vast range combinations of materials is available for use in composites.

For example, carbon fiber reinforced frames for tennis rackets and shafts for golf clubs have revolutionized these sports.

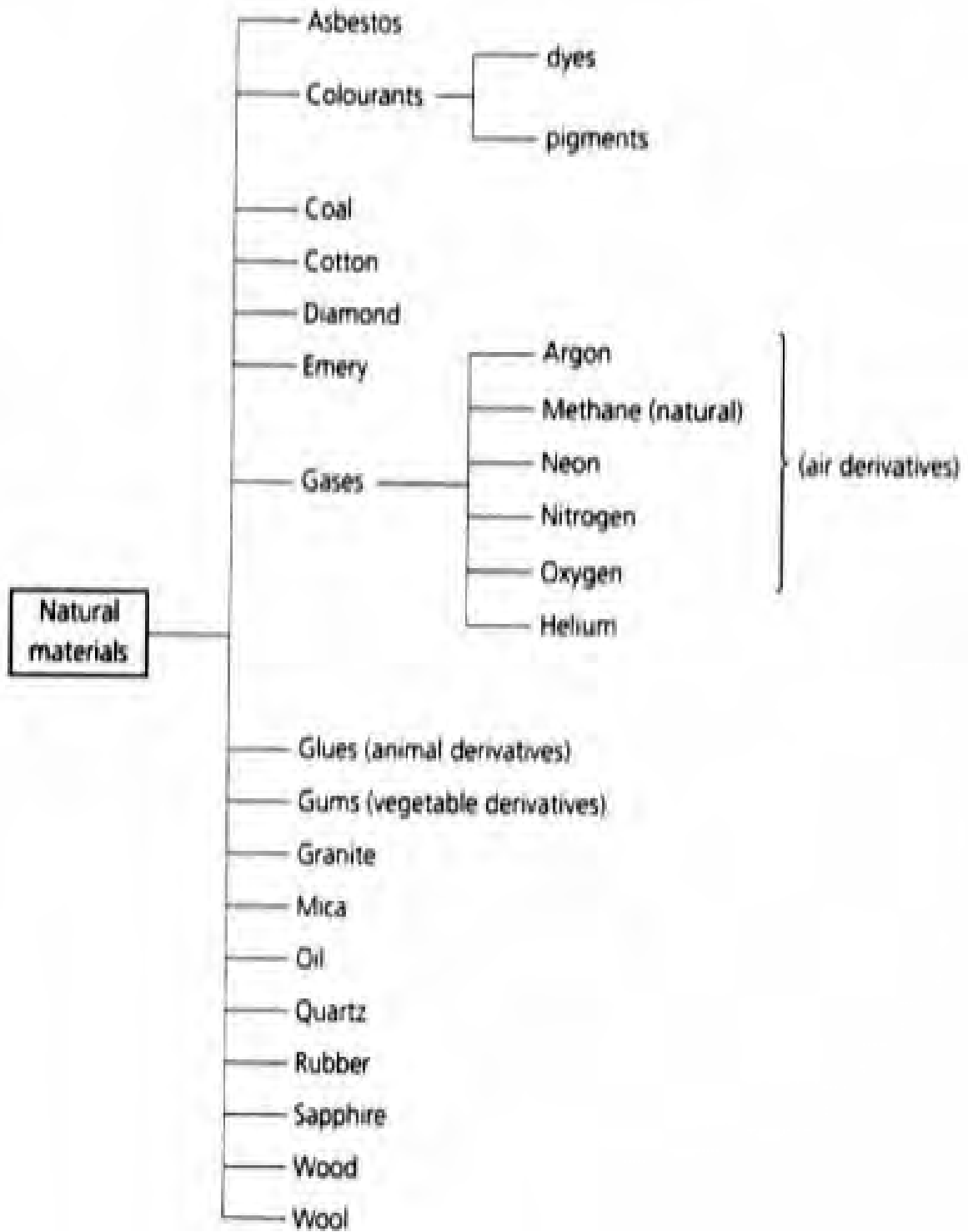


Figure 7. Classification of natural materials.

Factors affecting materials properties:

The following are the more important factors which can be influence the properties and performance of engineering materials.

1. Heat treatment

This is the controlled heating and cooling of metals to change their properties to improve their performance or to facilitate processing.

An example of heat treatment is the hardening of a piece of high-carbon steel rod. If it is heated to dull red heat and plunged into cold water to cool it rapidly (quenching), it will become hard and brittle. If it is again heated to dull red heat but allowed to cool *very slowly* it will become softer and less brittle (more tough). In this condition it is said to be *annealed*.

After the heat treatment happened on the material it will be in its best condition for flow forming, during flow forming (working) the grains will be distorted and this will result in most metals becoming *work hardened* if flow formed at room temperature. To remove any locked in stresses resulting from the forming operations and to prepare the material for machining, the material has to be *normalized*.

2. Processing

Hot –and cold working process will be referred to understand what is meant by terms hot and cold working as applied to metals. Figure 8 shows examples of hot and cold working.

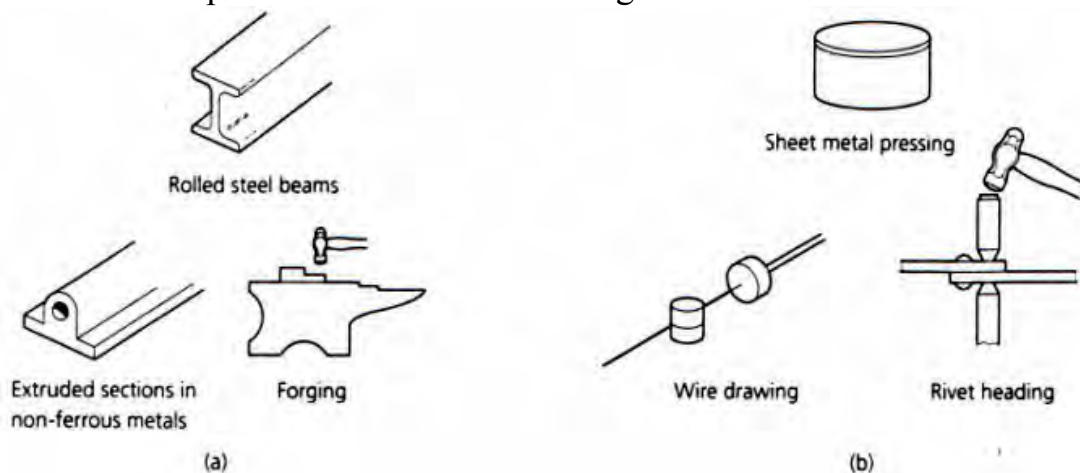


Figure 8. Examples of (a) hot-working and (b) cold-working process.

Metal is hot worked or cold worked depending upon the temperature at which it is flow formed to shape. These temperatures are not easy to define. For instance, lead hot works at room temperature and can be beaten into complex shapes without cracking, but steel does not hot work until it is red hot.

When metal are examined under the microscope it can be seen that they consist of very small grains. When most metals are bent or worked

at room temperature (cold worked) these grains become distorted and the metal becomes hard and brittle .

When metals are hot worked the crystals are also distorted. however, they reform instantly into normal crystals because the process temperature is above the temperature of recrystallisation for the metal being used and work hardening does not occur. this cold working is the flow forming of metals below the temperature the recrystallisation, whilst hot working is the flow forming of metals above the temperature of recrystallisation.

3. Environmental reactions

The properties of materials can also be effected by reaction with environment in which they are used. For example:

Resting of steel

Unless steel structures are regularly maintained by rest neutralization and painting process, resting will occur. The rest will eat into the steel, reduce its thickness and, therefore, its strength. In extreme cases an entire structure made from steel may be eaten away.

Dezincification of brass

Brass is an alloy of copper and zinc and when brass is exposed to a **marine** environment for along time, the salt in the sea water pray react with the zinc content of the brass so as remove it and leave it behind on spongy, porous mass of copper. This obviously weakness the material which fails under normal working conditions.

Degradation of plastic

Many plastic degrade and become weak and brittle when exposed to the ultraviolet content of sunlight. Special dyestuffs have to be incorporated into the plastic to filter out these harmful rays.

Engineering Materials

2

Metal Structure and Bonding in Materials :

Introduction:-

Although the properties of the metals used widely they all had one thing in common. No matter what their composition, no matter what changes they had gone through during extraction from the ore, refinement and processing, they were all crystalline.

Atoms:-

Not so very long ago, in our early chemistry lessons, we used to say that the atom was the smallest unit of which matter was composed and was indivisible. Also the atom is considered as the basic structural unit of matter. Now, it is not quite so simple as that, and the chemist no longer regards the atom as being in the nature of an indestructible little billiard-ball which is held by some mysterious force of attraction to its neighbors.

Each atom is composed of a positively charged **nucleus** surrounded by a sufficient number of negatively charged **electrons** so that the charges are balanced and **neutrons** which carry no charge. The number of electrons identifies the atomic number and the element of the atom.

When the atoms have gained or lost one or more electrons, it is called as " **Ions**". Losing of an electron makes the atom *electropositive* since there will be a positively charged proton without its balancing electron. Such an ion is called a **positive ion**. While gaining an electron makes the atom *electronegative* since there is no spare positively charged proton in the nucleus to balance the additional electron. Such an ion is called a **negative ion**.

Chemical properties are related to the numbers of electrons and protons present and in this respect there are altogether ninety-two basically different types of atom which occur naturally. Of late the scientists have succeeded in building up a series of new ones.

When two or more atoms, either of one type or of different types, are joined together chemically, the unit which is produced is called a molecule.

In a similar way the gases fluorine and chlorine, with seven electrons in the outer shell in each case, have like chemical properties. Both are gases

(at normal temperatures and pressures) with strongly non-metallic properties.

Many of the similarities and differences among the elements can be explained by their respective atomic structures as shown in Figure 1.

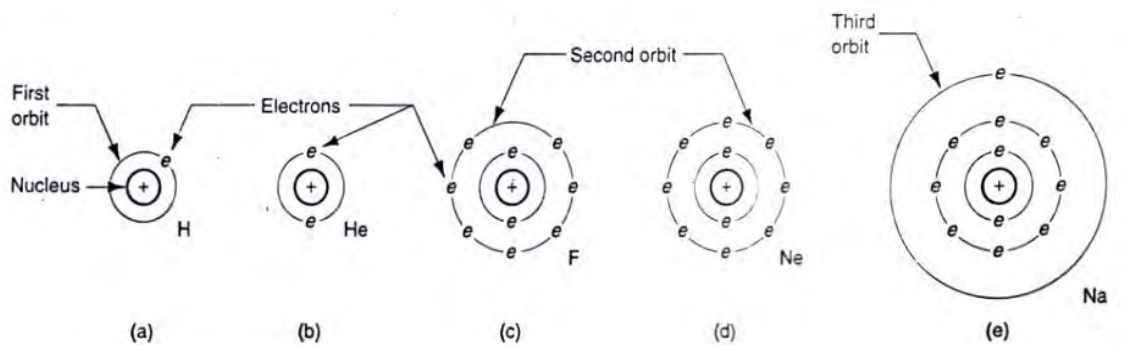


Figure 1. Simple model of atomic structure for several elements :
(a) hydrogen , (b) helium, (c) fluorine, (d) neon, (e) sodium.

We might infer that there is a maximum number of electrons that can be contained in a given orbit. This turns out to be correct, and the maximum is defined by:

$$\text{Maximum number of electrons in an orbit} = 2n^2$$

where n identifies the orbit, with $n = 1$ closest to the nucleus.

The number of electrons in the outermost shell, relative to the maximum number allowed, determines to a large extent the atom's chemical affinity for other atoms. These outer shell electrons are called *valence electrons*. For example, since a hydrogen atom has only one electron in its single orbit, it readily combines with another hydrogen atom to form a hydrogen molecule H_2 . For the same reason, hydrogen also reacts readily with various other elements (for example, to form H_2O). In the helium atom, the two electrons in its only orbit are the maximum allowed [$2n^2 = 2(1)^2 = 2$]. and so helium is very stable. Neon is stable for the same reason. Its outermost orbit ($n = 2$) has eight electrons (the maximum allowed), so neon is an inert gas.

In contrast to neon, fluorine has one fewer electron in its outer shell ($n = 2$) than the maximum allowed and is readily attracted to other elements that might share an electron to make a more stable set. The sodium atom seems divinely made for the situation, with one electron in its outermost orbit. It reacts strongly with fluorine to form the compound sodium fluoride, as pictured in Figure 2.

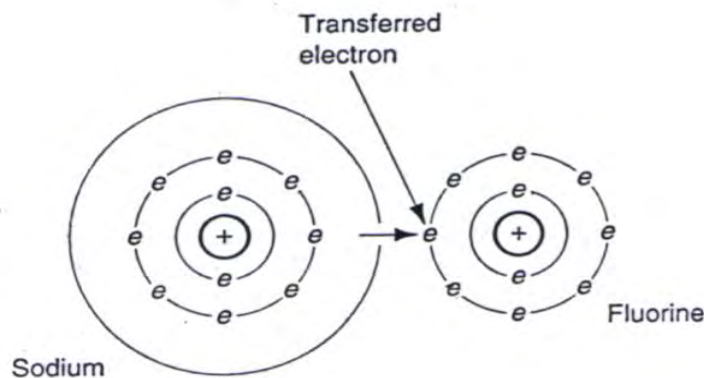


Figure 2. The sodium fluoride molecule, formed by the transfer of the extra electron of the sodium atom to complete the outer orbit of the fluorine atom.

At the low atomic numbers considered here, the prediction of the number of electrons in the outer orbit is straightforward. As the atomic number increases to higher levels, the allocation of electrons to the different orbits becomes somewhat more complicated.

Bonding in Materials:

It depends on the bonding between atoms and molecules where the atoms are held together in molecules by various types of bonds that depends on the valence electrons. By comparison, molecules are attracted to each other by weaker bonds, which generally result from the electron configuration in the individual molecules.

Thus, we have the following types of bonding:

1. Ionic Bond

In the *ionic bond*, the atoms of one element give up their outer electron(s), which in turn are attracted to the atoms of some other element to increase their electron count in the outermost shell to eight, as shown in figure 3. This bond naturally provides a very strong bond between atoms and as a properties of solid materials with the ionic bonding include low electrical conductivity and poor ductility.

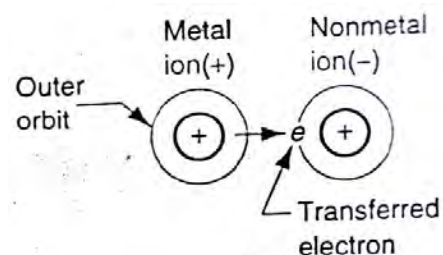
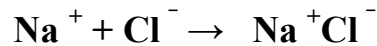


Figure 3. Ionic bond.

As an example of this bond is the Sodium chloride (table salt) is a more common example. Because of the transfer of electrons between the atoms, sodium and chlorine *ions* are formed as shown in this reaction :



2. Covalent Bond

In the *covalent bond*, electrons are shared (as opposed to transferred) between atoms in their outermost shells to achieve a stable set of eight, as shown in figure 4.

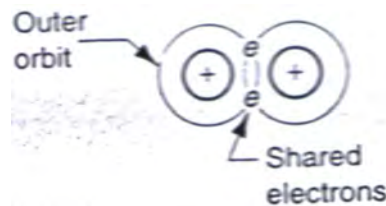


Figure 4. Covalent bond.

Solids with covalent bonding generally possess high hardness and low electrical conductivity. As an example of covalent bond the molecule of the gas methane (CH_4), four hydrogen atoms are combined with one carbon atom. The carbon atom has four electrons in its outer shell, but these are joined by four more electrons, contributed singly by each of the four hydrogen atoms as shown in figure 5.

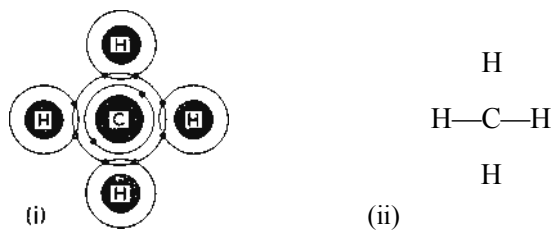


Figure 5. (i) Covalent Bonding in a Molecule of Methane, CH_4 .

(ii) Chemists express the structural formula for the methane molecule.

3. Metallic Bond

It is the atomic bonding mechanism in pure metals and metal alloys. The metallic bonding involves the sharing of outer shell electrons by all atoms to form a general electron cloud that permeates the entire block as shown in figure 6.

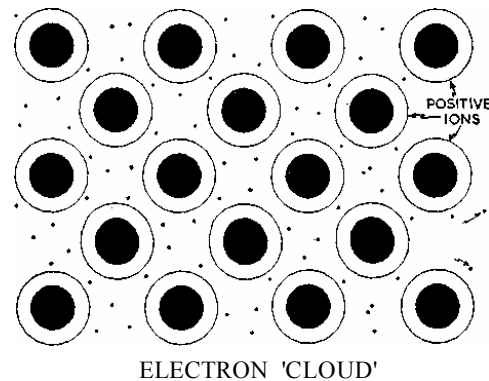


Figure 6 . Diagrammatic Representation of the "Metallic Bond".

This cloud provides the attractive forces to hold the atoms together and form a strong, rigid structure in most cases. Because of the general sharing of electrons and their freedom to move within the metal, metallic bonding provides typical properties of materials characterized such as good electrical conductivity , good conduction of heat and good ductility.

4. Van der Waal's Force

They are very small forces of attraction acting between atoms in cases where the formation of ionic or covalent bonds is not possible.

Basically similar forces also act between atoms which are already bounded in neighboring molecules , giving rise to weak Van der Waal's forces between long-chain molecules in polymers.

Crystalline Structures :

Many substances, including metals, have a crystalline structure in the solid state. Metal crystals form when the molten metals cool and solidifies, whereas crystals of other substances, for example copper sulphate, and sodium chloride (salt), form when a saturated solution of compound evaporates causing the solid to crystallize out.

In crystalline structure , the atoms are located at regular and recurring positions in three dimension . The pattern may be replicated millions of times within a given crystal. The structure can be viewed in the form of a *unit cell*, which is the basic geometric grouping of atoms that is repeated.

There are several types of pattern in which metallic atoms can arrange themselves on solidification, but the most common is as follows :-

1. Body-Centered-Cubic [BCC]

As shown in figure 7 (a), as an example of the materials for this type :

Chromium, Molybdenum, Niobium, Tungsten, Iron.

2. Face-Centered-Cubic [FCC]

As shown in figure 7 (b), as an example of the materials for this type :

Aluminum, Copper, Lead, Nickel, Iron, Gold, Silver.

3. Hexagonal-Closed-Packed [HCP]

As shown in figure 7 (c), as an example of the materials for this type :

Beryllium, Cadmium, Magnesium, Zinc.

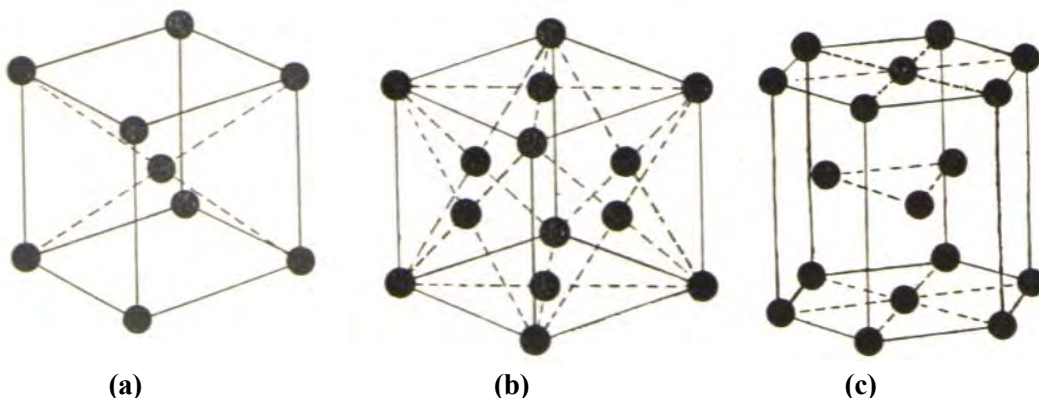


Figure 7 The three principle types of structural in which metallic elements crystallize :
(a) Body-Centered-Cubic (b) Face-Centered-Cubic (c) Hexagonal-Closed-Packed.

There are some metals that are undergo a change of structure at different temperatures. Iron metal for example is arranged in a body-centered-cubic (BCC) at room temperature, when the metal is heated and reaches a temperature of 910°C , the atoms rearrange themselves into Face-Centered-Cubic (FCC) crystals. If the metal is heated to the still higher temperature of 1400°C the atoms again rearrange themselves, this time back into Body-Centered-Cubic form.

Noncrystalline (Amorphous) Structures:

The noncrystalline solids materials do not have their basic particles arranged in a geometric pattern. Their particles have a random formation, and such as a result, such substances are said to be amorphous (without shape).

Many important materials are noncrystalline: liquids and gases, for example. Water and air have a noncrystal structures. A metal loses its crystalline structure when it is melt. Such as glass, plastics and rubber are materials that fall into this category. While many important plastics are mixture of crystalline and noncrystalline forms.

Two closely related features differentiate noncrystalline from crystalline materials :-

1. Absence of long – range order in the molecular structure of a noncrystalline. It can be visualized with reference to figure 8. They closely packed and repeating pattern of the crystal structure and random arrangement of atoms in the noncrystalline materials.

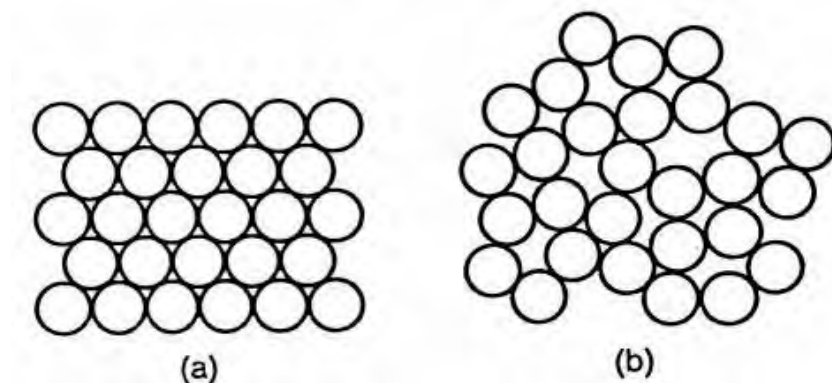


Figure 8. Difference in structure between (a) crystalline and (b) noncrystalline materials.

2. Differences in melting and thermal expansion characteristics. It could be demonstrated by a metal when it is melts. When the metal is molten an increase in volume compared to the material's solid crystalline state. This effect is characteristic most materials when melted (a noble exception is ice; liquid water is denser than ice).

The crystalline state :

As we mention before, that all of the metals and its alloys have crystalline structure where the atoms are rearranged in an organized shapes which it is called as the crystal lattice. This lattice consisted of another smallest grouping of atoms each one is called the unit cell as shown in figure 9.

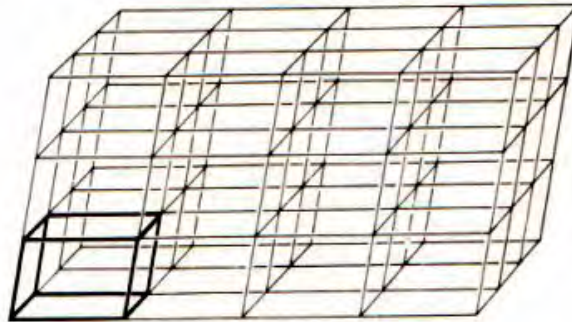


Figure 9. Representation of part of a space lattice with a unit cell outlined.

The unit cell is the smallest parallel surfaces of the crystalline structure that can be removed or repeated in different directions. It is also differ from each other in shape or size in the crystalline lattice from one material to another.

The atoms that belongs to the unit cell are called the basic atoms, its number is different from one shape of arrangement to another, this number can be found from the following equation:-

$$N = N_C + N_I + N_F$$

where N : is the number of the basic atoms in the unit cell.

N_C : is the number of the atoms in the corner.

N_I : is the number of the atoms in side the cube.

N_F : is the number of the atoms in the center of the face.

For the Body-centered-cubic (BCC), it is obvious that the unit cell have just two atoms the first one in the corner of the cube and the second in the center of the cube (that share the unit cell with each atom in the corner) as in the equation:

$$N = 8 * 1/8 + 1 = 2$$

As for the Face-centered-cubic (FCC) it is calculated by the equation below:

$$N = 8 * 1/8 + 6 * 1/2 = 4$$

Finally for the Hexagonal-closed-packed (HCP) is also calculated as follows :

$$N = 12 * 1/6 + 3 + 2 * 1/2 = 6$$

The atomic packing factor [A.P.F]:

It can be defined as the ratio between the volume of the basic atoms of the unit cell (which represent the volume of all atoms in one unit cell) to the volume of the unit cell itself.

For cubic crystals, there is one constant to be quoted. The unit cell constant of pure metal crystals can be directly related to the atomic diameter of the element as below:-

1. Body-centered-cubic (BCC)

In the body centered cubic the length of the cube diagonal = $2D$, as shown in figure 10, and by Pythagoras :

$$(2D)^2 = a^2 + 2a^2$$

$$\Rightarrow D = \frac{\sqrt{3}}{2}a \quad \& \quad r = \frac{D}{2}$$

$$\Rightarrow r = \frac{\sqrt{3}}{4}a$$

The volume of the atom can be calculated as follows :

$$V = \frac{4}{3} \Pi r^3 = \frac{4}{3} \Pi \left(\frac{\sqrt{3}}{4} a \right)^3$$

The volume of the basic atoms in the unit cell can be calculated as follows :

$$V_b = 2 \left[\frac{4}{3} \Pi \left(\frac{\sqrt{3}}{4} a \right)^3 \right]$$

The volume of the unit cell is $V_u = a^3$

$$A.P.F. = \frac{V_b}{V_u} = \frac{2 \left[\frac{4}{3} \Pi \left(\frac{\sqrt{3}}{4} a \right)^3 \right]}{a^3} = 0.68$$

where D : is the atomic diameter

a : is the lattice constant

r : is the atomic radius

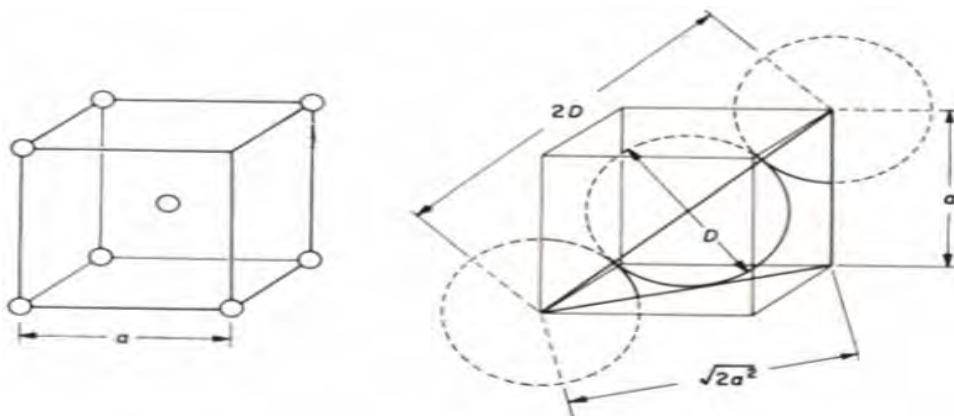


Figure 10. Body centered cubic unit cell. Relation between a and D .

2. Face-centered-cubic (FCC)

Similarly, for face centered cubic as shown in figure 11, the length of a face diagonal = $2D$ and by Pythagoras:

$$(2D)^2 = a^2 + a^2$$

$$\Rightarrow D = \frac{1}{\sqrt{2}}a \quad \& \quad r = \frac{D}{2}$$

$$\Rightarrow r = \frac{1}{2\sqrt{2}}a$$

The volume of the basic atoms in the unit cell can be calculated as follows :

$$V_b = 4 \left[\frac{4}{3} \Pi \left(\frac{1}{2\sqrt{2}}a \right)^3 \right]$$

The volume of the unit cell is : $V_u = a^3$

$$A.P.F. = \frac{4 \left[\frac{4}{3} \Pi \left(\frac{1}{2\sqrt{2}}a \right)^3 \right]}{a^3} = 0.74$$

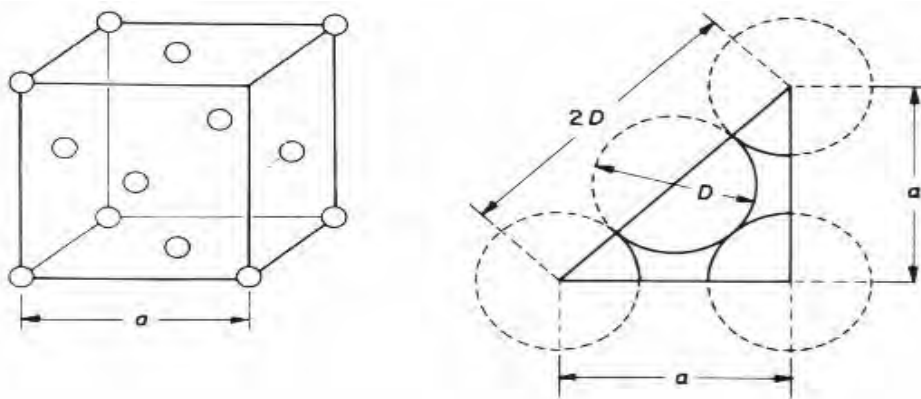


Figure 11. Face centered cubic unit cell. Relation between a and D .

3. Hexagonal-closed-packed (HCP)

There are two lattice constant, a and c as shown in figure 12, that parameter a is equal to one atomic diameter [$a = D$], the parameter c is the high of the hexagonal structure.

From the hexagonal structure basics :

$$\frac{c}{a} = 1.633 \quad , \quad r = \frac{a}{2}$$

so the volume of the basic atoms is :

$$V_b = 6 \left[\frac{4}{3} \Pi \left(\frac{a}{2} \right)^3 \right] = \Pi a^3$$

and the volume of the unit cell is :

$$V_u = \frac{3\sqrt{3}}{2} a^2 \cdot c = \frac{3\sqrt{3}}{2} \times 1.633 a^3$$

$$A.P.F. = \frac{\Pi a^3}{\frac{3\sqrt{3}}{2} \times 1.633 a^3} = 0.74$$

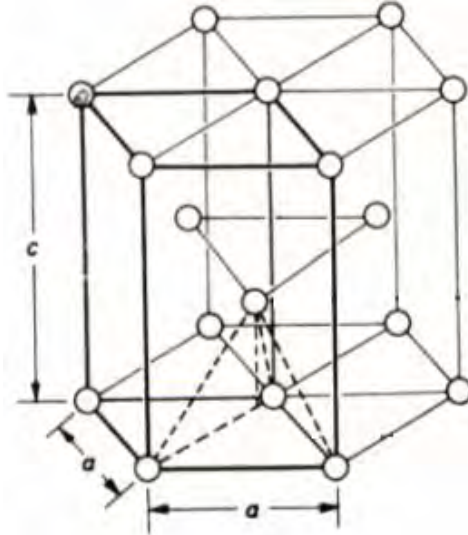


Figure 12. Hexagonal structure with unit cell outlined, and showing relationship between a and c.

Example :

The atomic radius of an iron atom is 1.238×10^{-10} m. Iron crystallizes as BCC. Calculate the lattice parameter of the unit cell, a. How many atoms are contained within the BCC unit cell ? Also find the atomic packing factor ?

For BCC unit cell

$$a = \frac{4}{\sqrt{3}} r$$

For iron $r = 1.238 \times 10^{-10}$ m

Therefore

$$a = \frac{4 \times 1.238 \times 10^{-10}}{\sqrt{3}} = 2.861 \times 10^{-10} \text{ m}$$

There are 9 atoms 8 in the corners and 1 in the center of the cubic.

And the

$$A.P.F. = \frac{V_b}{V_u} = \frac{2 \left[\frac{4}{3} \Pi \left(\frac{\sqrt{3}}{4} a \right)^3 \right]}{a^3} = 0.68$$

Engineering Materials

3

General Properties of Engineering Materials

The principle properties of materials which are of importance to the engineer in selecting materials. These can be broadly divided into:

Physical properties of materials

These properties concerned with such properties as melting, temperature, electrical conductivity, thermal conductivity, density, corrosion resistance, magnetic properties, etc. and the more important of these properties will be considered as follows :

1. Density

Density is defined as mass per unit volume for a material. The derived unit usually used by engineers is the kg/m^3 . Relative density is the density of the material compared with the density of the water at 4°C . The formulae of density and relative density are:

$$\text{density } (\rho) = \frac{\text{mass } (m)}{\text{volume } (V)}$$

$$\text{Relative density } (d) = \frac{\text{Density of the material}}{\text{Density of pure water at } 4^\circ\text{C}}$$

2. Electrical conductivity

Figure 1 shows a piece of electrical cable. In this example copper wire has been chosen for the conductor or core of the cable because copper has the property of very good electrical conductivity. That is, it offers very little resistance to the flow of electrons (electric current) through the wire. A plastic materials such as polymerized has been chosen for the insulating sheathing surrounding the wire conductor. This material has been chosen because it is such a bad conductor, where very few electrons can pass through it. Because they are *very bad conductors* they are called as *insulators*. There is no such thing as a perfect insulator, only very bad conductors.

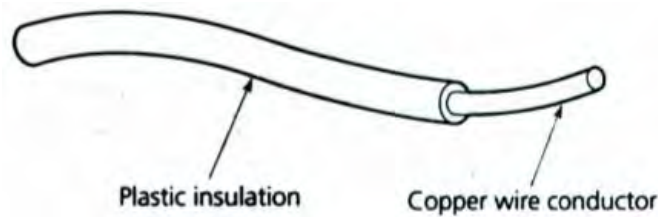


Figure 1. Electrical conductivity.

For example, metallic conductors of electricity all increase in resistance as their temperatures rise. Pure metal shows this effect more strongly than alloys. However, pure metals generally have a better conductivity than alloys at room temperature. The conductivity of metals and metal alloys improves as the temperature falls.

Conversely, non-metallic materials used for insulators tend to offer a lower resistance to the passage of electrons, and so become poorer insulators, as their temperatures rise. Glass, for example, is an excellent insulator at room temperature, but becomes a conductor if raised to red heat.

3. Melting temperature of material

The melting temperatures and the recrystallisation temperatures have a great effect on the materials and the alloys of the materials properties and as a result on its applications.

4. Semiconductors

So far we have examined the conductivity of the metals and the insulating properties of the non-metals (exception : carbon). In between conductors and insulators lies a range of materials known as semiconductors. These can be good or bad conductors depending upon their temperatures. The conductivity of semiconductor materials increases rapidly for relatively small temperature increases. This enable them to be used as temperature sensors in electronic thermometers.

Semiconductor materials are capable of having their conductors properties changed during manufacture. Examples of semiconductor materials are **silicon** and **germanium**. They are used extensively in the electronics industry in the manufacture of solid-state devices such as diodes, thermistors, transistors and integrated circuits.

5. Thermal conductivity

This is the ability of the material to transmit heat energy by conduction. Figure 2 shows a soldering iron. The bit is made from copper which is a good conductor of heat and so will allow the heat energy stored in it to travel easily down to the tip and into the work being soldered. The wooden handle remains cool as it has a low thermal conductivity and resists the flow of heat energy.

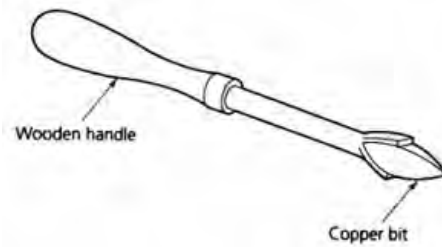


Figure 2. Thermal conductivity.

6. Fusibility

This is the ease with which materials will melt. It can be seen from figure 3 that solder melts easily and so has the property of *high fusibility*. On the other hand, fire bricks used for furnace linings only melt at very high temperatures and so have the properties of *low fusibility*. Such materials which only melt at very high temperatures are called *refractory materials*. These must not be confused with materials which have a low thermal conductivity and used as thermal insulators. Although expanded polystyrene is an excellent thermal insulator, it has a very low melting point (high fusibility) and in no way can it be considered a refractory material.

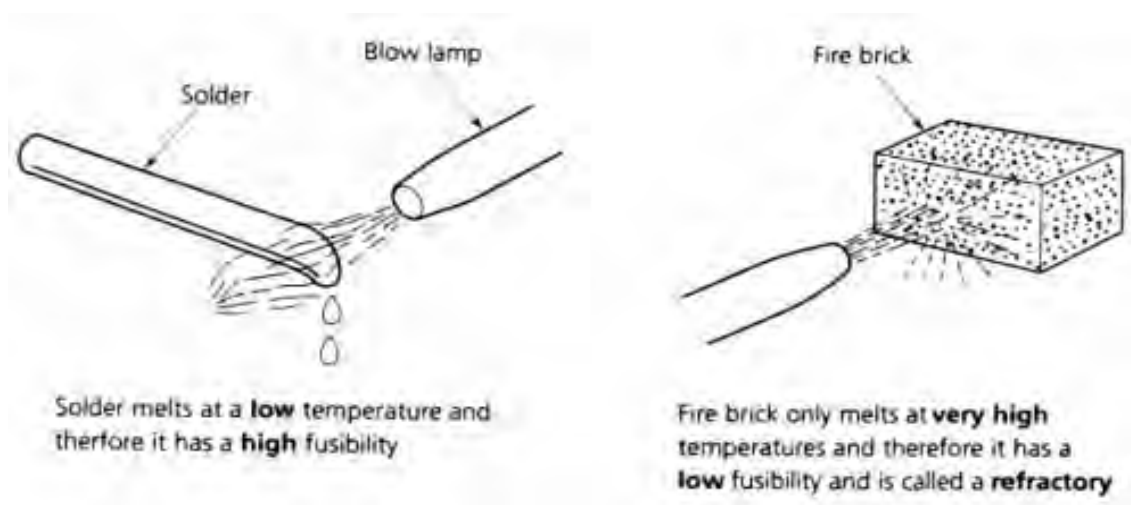


Figure 3. Fusibility.

7. Reluctance (as magnetic properties)

Just as some materials are good or bad conductors of electricity, some materials can be good or bad conductors of magnetism. The resistance of *magnetic circuit* is referred to as *reluctance*. The good magnetic conductors have low reluctance and examples are the ferromagnetic materials which get their name from the fact that they are made from iron, steel and associated alloying elements such as cobalt and nickel. All other materials are non-magnetic and offer a high reluctance to the magnetic flux field.

8. Temperature stability

Any changes in temperature can have very significant effects on the structure and properties of materials. However, there are several effects can appear with changes in temperature such as *creep*.

Creep is defined as the gradual extension of a material over a long period of time whilst the applied load is kept constant. It is also an important factor when considering plastic materials, and it must be considered when metals work continuously at high temperatures. For example gas-turbine blades. The creep rate increases if the temperature is raised, but becomes less if the temperature is lowered.

Mechanical properties of materials

These properties are concerned with the following properties :

1. Tensile strength TS

It is the ability of a material to withstand tensile (stretching) loads without breaking. For example, figure 4 shows a heavy load being held up by a rod fastened to beam. As the force of gravity acting on the load is trying to stretch the rod, the rod is said to be in tension. Therefore, the material from which the rod is made needs to have sufficient tensile strength to resist the pull of the load.

Strength: is the ability of a material to resist applied forces without fracturing.

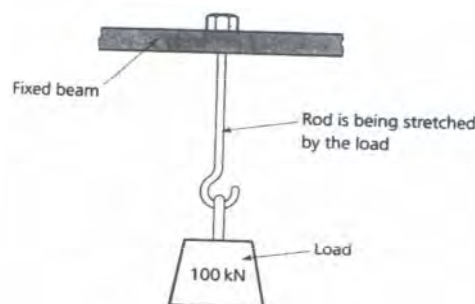


Figure 4. Tensile Strength

2. Toughness

It is the ability of the materials to withstand bending or it is the application of shear stresses without fracture, so the rubbers and most plastic materials do not shatter, therefore they are tough. For example, if a rod is made of high-carbon steel then it will be bend without breaking under the impact of the hammer, while if a rod is made of glass then it will broken by impact loading as shown in figure 5.

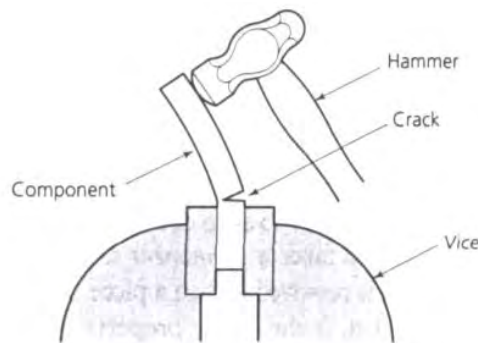


Figure 5. Toughness (Impact Resistance).

3. Malleability

It is the capacity of substance to withstand deformation under compression without rupture or the malleable material allows a useful amount of plastic deformation to occur under compressive loading before fracture occurs. Such a material is required for manipulation by such processes as forging, rolling and rivet heading as shown in figure 6.

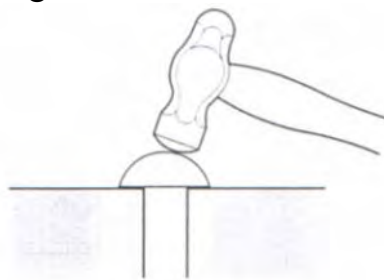


Figure 6. Malleability

4. Hardness

It is the ability of a material to withstand scratching (abrasion) or indentation by another hard body, it is an indication of the wear resistance of the material. For example, figure 7 shows a hardened steel ball being pressed first into a hard material and then into a soft material by the same load. As seen that the ball only makes a small indentation in the hard material but it makes a very much deeper impression in the softer material.

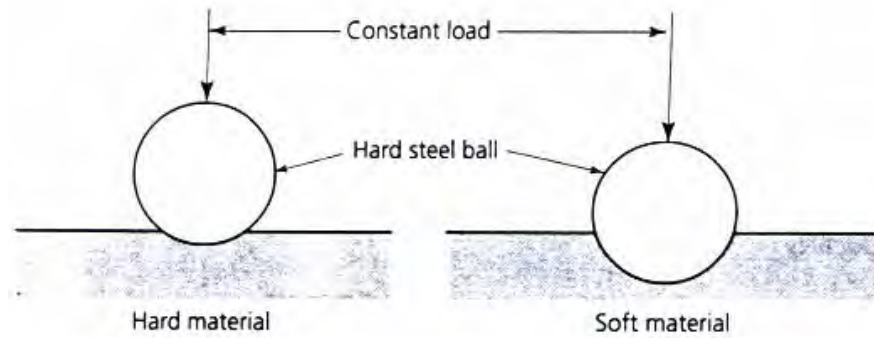


Figure 7. Hardness.

5. Ductility

It refers to the capacity of a substance to undergo deformation under tension without rupture as in wire drawing (as shown in figure 8), tube drawing operation.

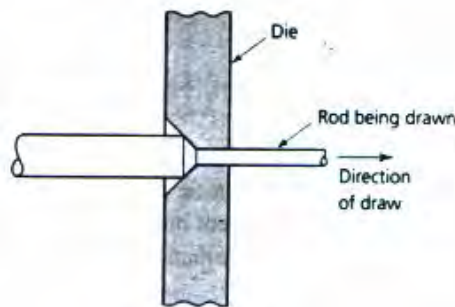


Figure 8. Ductility

6. Stiffness

It is the measure of a material's ability not to deflect under an applied load. For example, although steel is very much stronger than cast iron, then the cast iron is preferred for machine beds and frames because it is more rigid and less likely to deflect with consequent loss of alignment and accuracy.

Consider figure 9 (a): for a given load the cast iron beam deflects less than the steel beam because cast iron is a more rigid material. However, when the load is increased as shown in figure 9 (b), the cast iron beam will break, whilst the steel beam deflects a little further but does not break. Thus a material which is rigid is not necessarily strong.

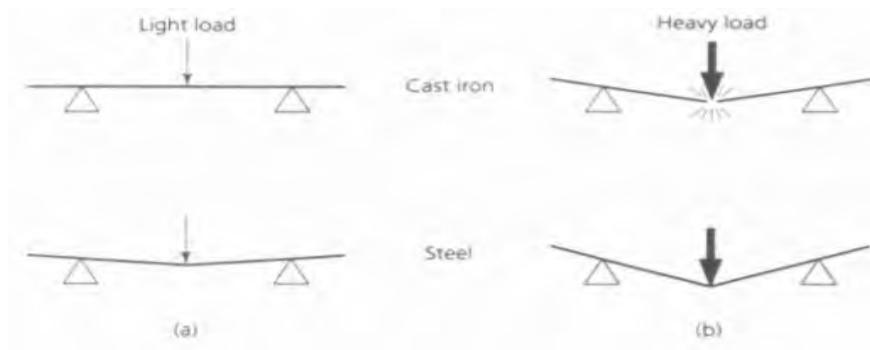


Figure 9. Stiffness (rigidity):

(a) The tested materials deflect under a light load

(b) The tested materials deflect under a heavy load.

7. Brittleness

It is the property of a material that shows little or no plastic deformation before fracture when a force is applied. Also it is usually said as the opposite of ductility and malleability.

8. Elasticity

It is the ability of a material to deform under load and return to its original size and shape when the load is removed. If it is made from an elastic material it will be the same length before and after the load is applied, despite the fact that it will be longer whilst the load is being applied. All materials possess elasticity to some degree and each has its own *elastic limits*. As in figure 10.

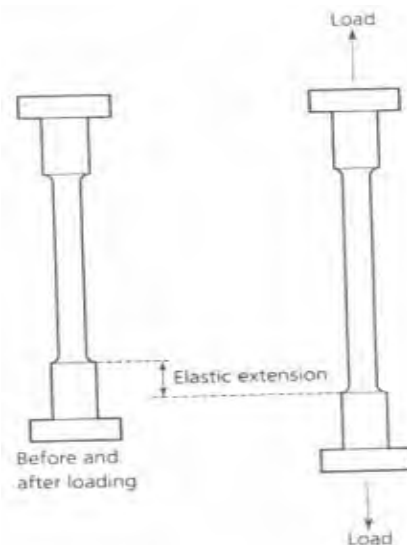


Figure 10. Elasticity.

9. Plasticity

This property is the exact opposite to elasticity, while the ductility and malleability are particular cases of the property of the plasticity . It is the state of a material which has been loaded beyond its elastic limit so as to cause the material to deform permanently. Under such conditions the material takes a permanent set and will not return to its original size and shape when the load is removed. When a piece of mild steel is bent at right angles into the shape of a bracket, it shows the property of plasticity since it dose not spring back strength again, this is shown in figure 11.

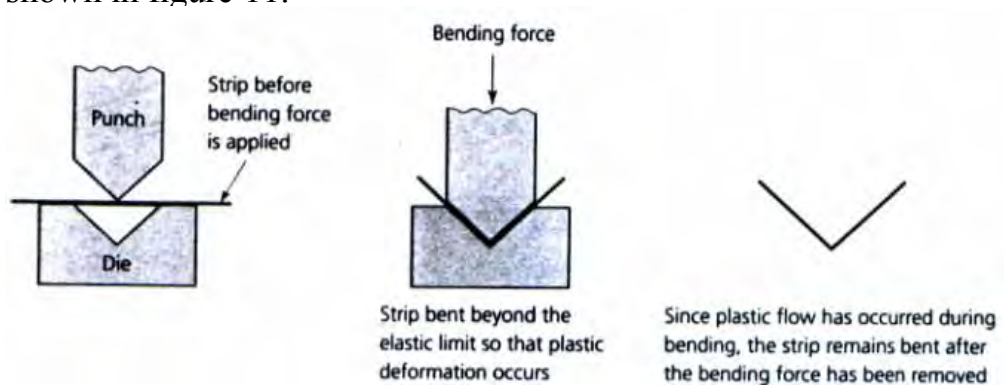


Figure 11. Plasticity.

Some metals such as lead have a good plastic range at room temperature and can be extensively worked (where working of metal means squeezing, stretching or beating it to shape). This is advantage for plumber when beating lead flashings to shape on building sites.

Engineering Materials

4

Materials Testing

Introduction:

Testing of materials are necessary for many reasons, and the subject of materials testing is very broad one. Some of the purpose for the testing of materials are:

1. To determine the quality of a material. This may be one aspect of process control in production plant.
2. To determine such properties as strength, hardness, and ductility.
3. To check for flaws within a material or in a finished component.
4. To assess the likely performance of the material in a particular service condition.

It is obvious that there is not one type of test that will provide all the necessary information about a material and its performance capabilities, and there are very many different types of test that have been devised for use in the assessment of materials. One of the most widely tests is the tensile test to destruction. In this type of test a test-piece of standard dimensions is prepared, and this is then stressed in uniaxial tension. Other tests that are often used for the determination of strength data are compression, torsion, hardness, creep and fatigue tests. With the exception of hardness tests, these are all test of a destructive nature and they normally require the preparation of test-pieces to certain standard dimensions.

For the detection of flaws or defects within part-processed stock material, or within finished components, there are several non-destructive test techniques available. In addition, there are many special tests that have been devised for the purpose of assessing some particular quality of material, or for obtaining information on the possible behavior of component or assembly in service.

In spite of the properties of materials where introduced, then the composition, processing and heat treatment of a range of metallic and non-metallic materials widely used by the engineer have been described, we should more be able to understand the problems and techniques associated with the testing of materials properties because they can be, nonetheless, useful to the designer, fabricator, and research worker, as follow:

1. Tensile test

The main principle of the tensile test is denotes the resistance of a material to a tensile load applied axially to a specimen.

There are a several tensile testing machine, as in figure 1 (a) shows a popular bench-mounted tensile testing machine, whilst figure 1(b) shows a more sophisticated machine suitable for industrial and research laboratories, while in figure 1(c) shows the schematic drawing of a tensile – testing apparatus. These machines are capable of performing compression, shear and bending tests as well as tensile tests.

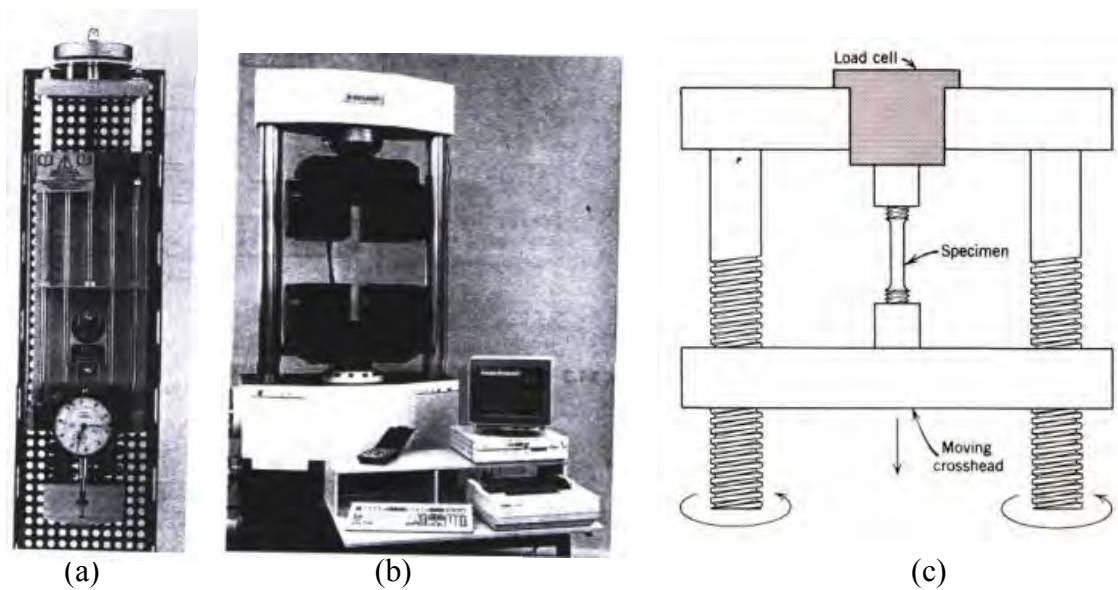


Figure 1. Tensile testing machines.

It is very important to the tensile test to be considered is the standard dimensions and profiles are adhered to.

The typical progress of tensile test can be seen in figure 2 .

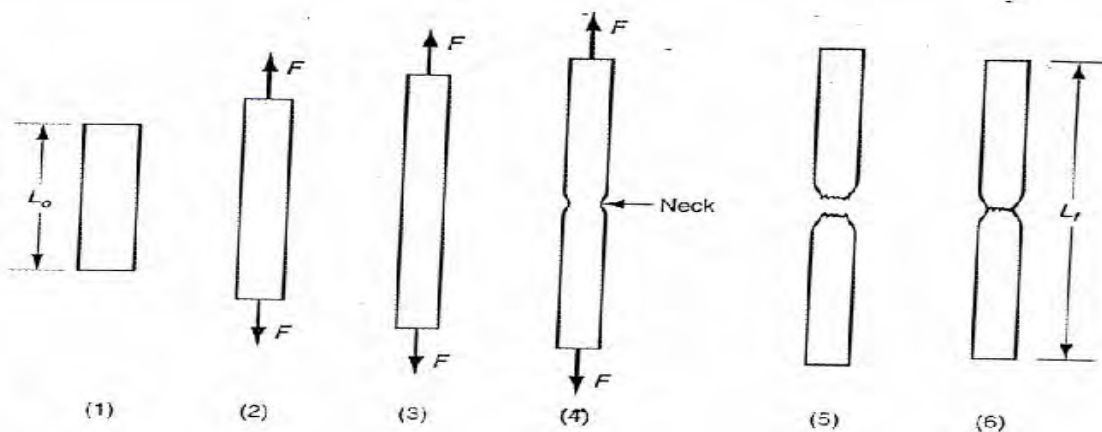


Figure 2. Typical progress of a tensile test: (1) beginning of test, no load; (2) uniform elongation and reduction of cross-sectional area; (3) continued elongation, maximum load reached; (4) necking begins, load begins to decrease; and (5) fracture. If pieces are put back together as in (6), final length can be measured.

Let's now look at Figure 3. In this figure, the *gauge length* (L_0) is the length over which the elongation of the specimen is measured. The *minimum parallel length* (L_c) is the minimum length over which the specimen must maintain a constant cross-sectional area before the test load is applied. The lengths L_0 , L_c , L_i , and the cross-sectional area (A) are all specified in BS 18.

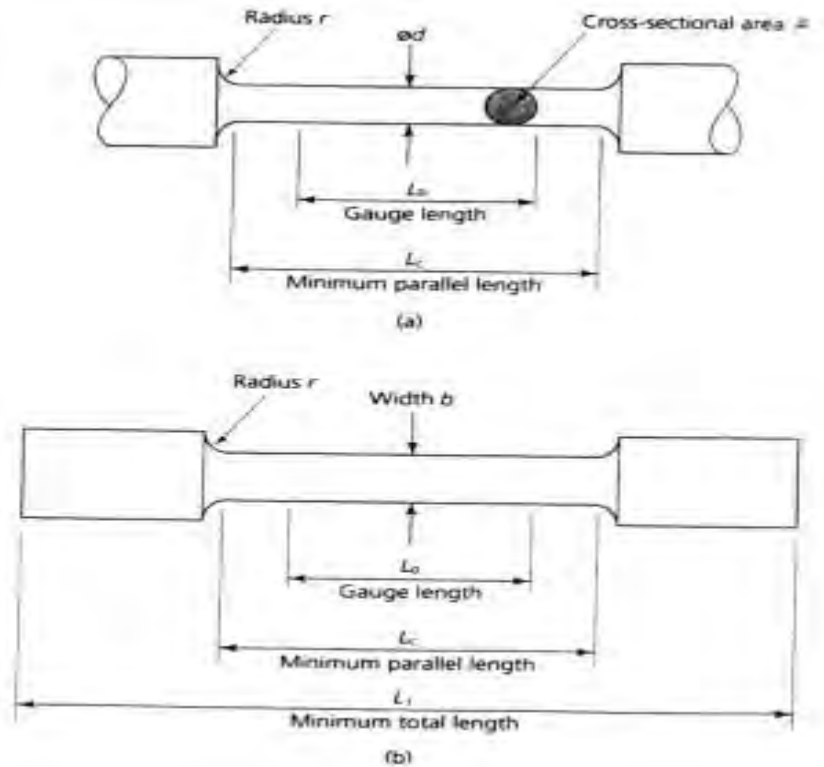


Figure 3. Properties of tensile test specimens: (a) cylindrical; (b) flat.

The elongation obtained for a given force depends upon the length and area of the cross-section of the specimen or component, since:

$$\text{elongation} = \frac{\text{applied force} \times L}{E \times A}$$

where L = length

A = cross-sectional area

E = elastic modulus

Therefore if the ratio $[L/A]$ is kept constant (as it is in a proportional test piece), and E remains constant for a given material, then comparisons can be made between elongation and applied force for specimens of different sizes.

Tensile test results:

Let's now look at the sort of results we would get from a typical tensile test on a piece of annealed low-carbon steel. The load applied to the specimen and the corresponding extension can be plotted in the form of a graph, as shown in Figure 4 .

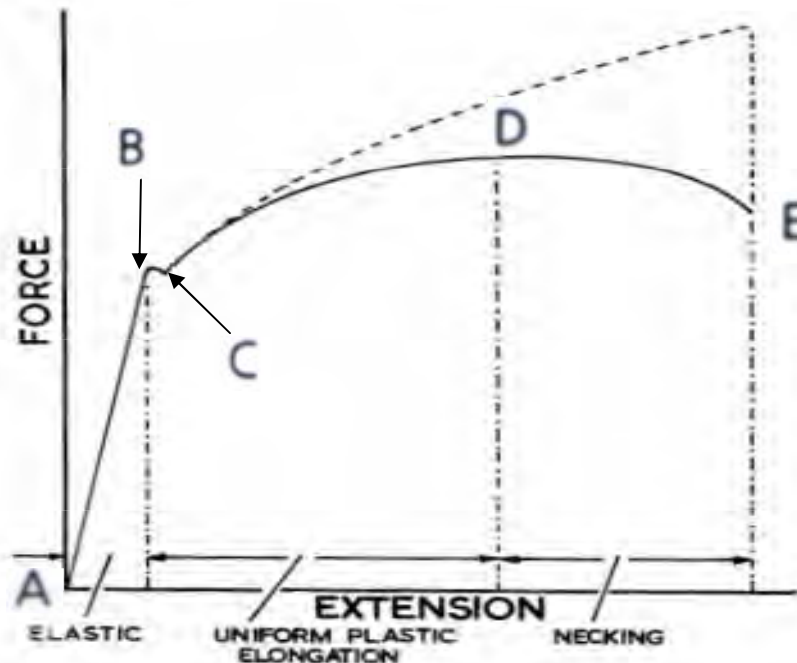


Figure 4. Load-extension curve for a low-carbon steel.

- From A to B the extension is proportional to the applied load. Also, if the load is removed the specimen returns to its original length. Under these relatively lightly loaded conditions the material is showing *elastic* properties.
- From B to C it can be seen from the graph that the metal suddenly extends with no increase in load. If the load is removed at this point the metal will not spring back to its original length and it is said to have taken a *permanent set*. Therefore, B is called "limit of proportionality", and if the force is increased beyond this point a stage is reached where a sudden extension takes place with no increase in force. This is known as the "*yield point*" C.
- The *yield stress* is the stress at the yield point; that is, the load at B divided by the original cross-section area of the specimen. Usually, a designer works at 50 per cent of this figure to allow for a 'factor of safety'.
- From C to D extension is no longer proportional to the load, and if the load is removed little or no spring back will occur. Under these relatively greater loads the material is showing *plastic* properties.
- The point D is referred to as the 'ultimate tensile strength' when referred extension graphs or the 'ultimate tensile stress' (UTS) when

referred to stress-strain graphs. The ultimate tensile stress is calculated by dividing the load at D by the original cross-sectional area of the specimen. Although a useful figure for comparing the relative strengths of materials, it has little practical value since engineering equipment is not usually operated so near to the breaking point.

- From D to E the specimen appears to be stretching under reduced load conditions. In fact the specimen is thinning out (necking) so that the 'load per unit area' or stress is actually increasing. The specimen finally work hardens to such an extent that it breaks at E.
- In practice, values of load and extension are of limited use since they apply to one particular size of specimen and it is more usual to plot the stress-strain curve.
- Stress and strain are calculated as follows:

$$\text{stress}(\sigma) = \frac{\text{load}}{\text{area of cross-section}}$$

$$\text{strain}(\varepsilon) = \frac{\text{extension}}{\text{original length}}$$

The tensile test experimental results on some materials:

The interpretation of tensile test data requires skill borne out of experience, since many factors can affect the test results - for instance, the temperature at which the test is carried out, since the tensile modulus and tensile strength decrease as the temperature rises for most metals and plastics, whereas the ductility increases as the temperature rises. The test results are also influenced by the rate at which the specimen is strained.

Figure 5 shows a typical stress-strain curve for an **annealed mild steel**. From such a curve we can deduce the following information.

- The material is ductile since there is a long elastic range.
- The material is fairly rigid since the slope of the initial elastic range is steep.
- The limit of proportionality (elastic limit) occurs at about 230 MPa.
- The upper yield point occurs at about 260 MPa.
- The lower yield point occurs at about 230 MPa.
- The ultimate tensile stress (UTS) occurs at about 400 MPa.

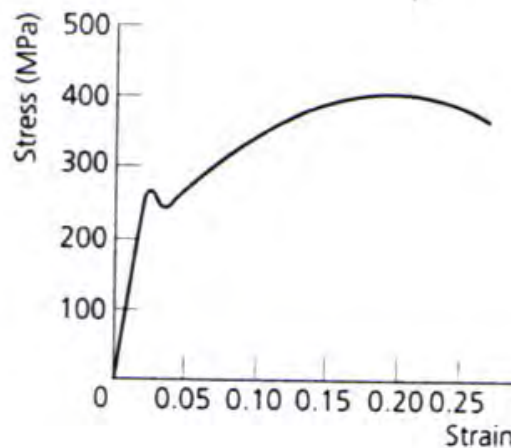


Figure 5. Typical stress-strain curve for annealed mild steel.

Figure 6 shows a typical stress-strain curve for a **grey cast iron**. From such a curve we can deduce the following information.

- The material is brittle since there is little plastic deformation before it fractures.
- A gain the material is fairly rigid since the slope of the initial elastic range is steep.
- It is difficult to determine the point at which the limit of proportionality occurs, but it is approximately 200 MPa.
- The ultimate tensile stress (UTS) is the same as the breaking stress for this sample. This indicates negligible reduction in cross-section (necking) and minimal ductility and malleability. It occurs at approximately 250 MPa.

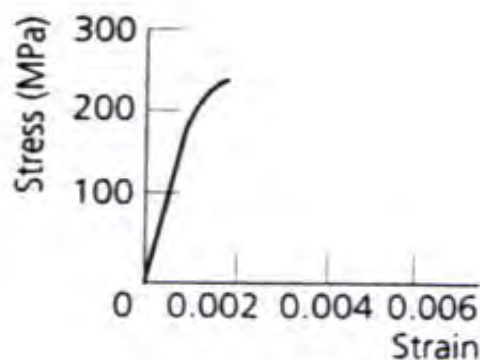


Figure 6. Typical stress-strain curve of grey cast iron.

The yield point, however, is possibly of greater importance to the engineer than the tensile strength itself, so it becomes necessary to specify a stress which corresponds to a definite amount of permanent extension as a substitute for the yield point. This is commonly called the "Proof Stress", and is derived as shown in figure 7. A line BC is drawn parallel to the line of proportionality, from a predetermined point B. the stress corresponding to C

will be the proof stress in the case illustrated it will be known as the "0.1 % Proof stress", since AB has been made equal to 0.1 % of the gauge length. The material will fulfil the specification therefore if, after the proof force is applied for fifteen seconds and removed, a permanent set of not more than 0.1 % of the gauge length has been produced. Proof lengths are commonly 0.1 % and 0.2 % of the gauge length, depending upon the type of alloy. The time limit of 15 seconds is specified in order to allow sufficient time for extension to be complete under the proffer force.

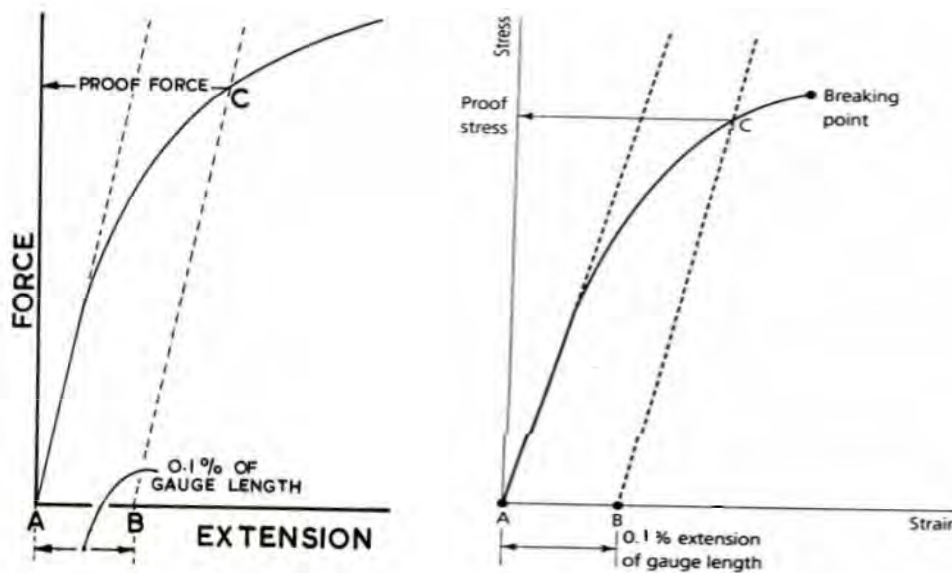


Figure 7. Method used to obtain the 0.1 % proof stress.

Figure 8 shows a typical stress-strain curve for a **wrought light alloy**. From this curve we can deduce the following information:

- The material has a high level of ductility since it shows a long plastic range.
- The material is much less rigid than either low-carbon steel or cast iron since the slope of the initial plastic range is much less steep when plotted to the same scale.
- The limit of proportionality is almost impossible to determine, so the proof stress will be specified instead. For this sample a 0.2 per cent proof stress is approximately 500 MPa (the line AB).

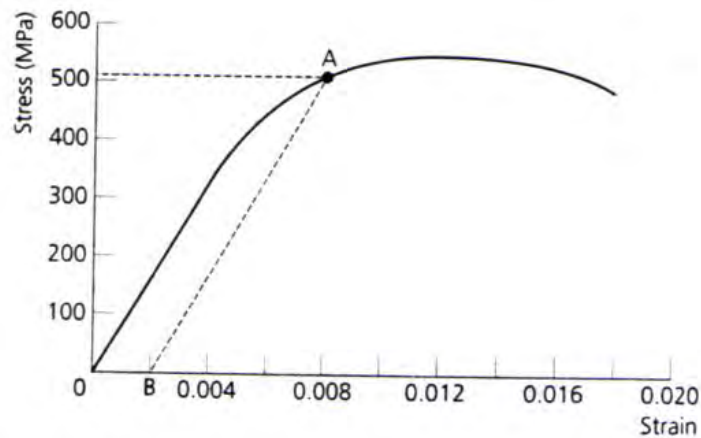


Figure 8. Typical stress-strain curve of a light alloy.

It is important to determine the properties of polymeric materials which are may ranged from highly plastic to the highly elastic. As in figure 9 the stress-strain curves for polymeric materials have been classified in to five main groups by **Carswell** and **Nason**.

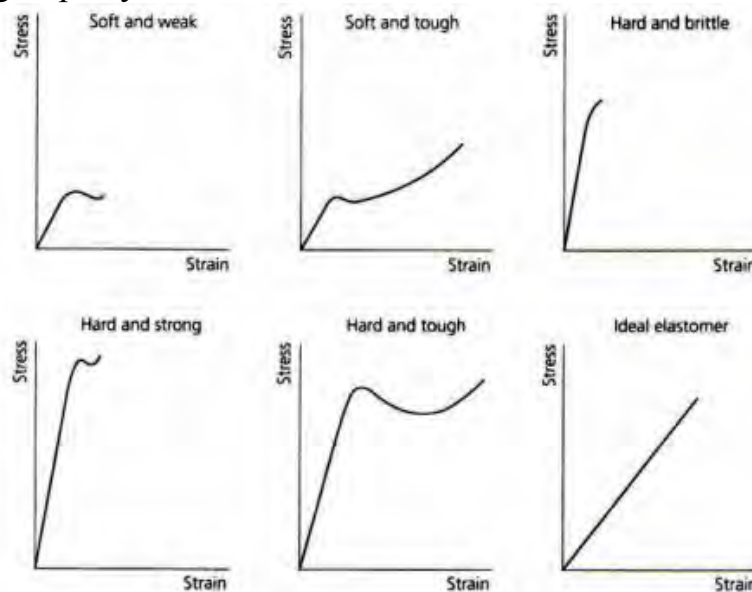


Figure 9. Typical stress-strain curves for polymers.

A tensile test can also yield other important facts about a material under test. For example, it can enable the elastic modulus (E) for the material to be calculated.

The physicist Robert Hooke found that within its elastic range the strain produced in a material is proportional to the stress applied. It was left to Thomas Young to quantify this law in terms of a mathematical constant for any given material.

$$\text{strain} \propto \text{stress}$$

therefore $\frac{\text{stress}}{\text{strain}} = \text{constant (E)}$

This constant term (E) is variously known as 'Young's modulus', the 'modulus of elasticity' or the 'tensile modulus'. Thus:

$$E = \frac{\text{tensile or compressive stress}}{\text{strain}}$$

$$= \frac{(\text{force})/(\text{original cross-sectional area})}{(\text{change in length})/(\text{original length})}$$

Example 1 :

Calculate the modulus of elasticity for a material which produces the following data when undergoing test:

Applied load = 35.7 kN, Cross-sectional area = 25mm²,
Gauge length = 28 mm, Extension = 0.2 mm.

$$E = \frac{\text{stress}}{\text{strain}}$$

Where

$$\text{stress } (\sigma) = \frac{35.7\text{kN}}{25\text{mm}} = 1.428 \text{ MPa}$$

and

$$\text{strain } (\epsilon) = \frac{0.2\text{mm}}{28\text{mm}} = 0.007$$

$$\text{therefore } E = \frac{35.7 \times 28}{25 \times 0.2} = 199.92 \text{ kN / mm}^2$$

$$= 200 \text{ GPa (approx.)}$$

This would be a typical value for a low-carbon steel.

It was stated earlier that malleability and ductility are special cases of the types of plasticity.

- *Malleability* This refers to the extent to which a material can undergo deformation in compression before failure occurs.
- *Ductility* This refers to the extent to which a material can undergo

deformation in tension before failure occurs.

All ductile materials are malleable, but not all malleable materials are ductile since they may lack the strength to withstand tensile loading.

Therefore ductility is usually expressed, for practical purposes, as the percentage; **Elongation** in gauge length of a standard test piece at the point of fracture when subjected to a tensile test to destruction.

$$\text{Elongation \%} = \frac{\text{increase in length}}{\text{original length}} \times 100$$

The increase in length is determined by fitting the pieces of the fractured specimen together carefully and measuring the length at failure.

$$\text{increase in length (elongation)} = \text{length at failure} - \text{original length}$$

Figure 10 shows a specimen for a soft, ductile material before and after testing. It can be seen that the specimen does not reduce in cross-sectional area uniformly, but that severe local necking occurs prior to fracture. Since most of the plastic deformation and, therefore, most of the elongation occurs in the necked region, doubling the gauge length does not double the elongation when calculated as a percentage of gauge length. Therefore it is important to use a standard gauge length if comparability between results is to be achieved.

Elongation is calculated as follows :

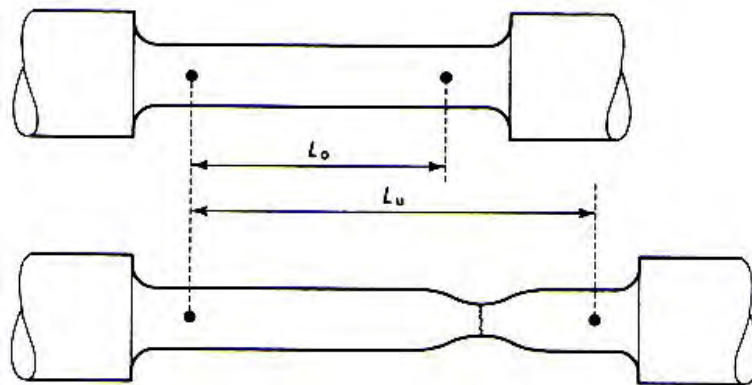


Figure 10. Elongation.

$$\text{Elongation \%} = \frac{L_u - L_o}{L_o} \times 100$$

Example 2:

Calculate the percentage elongation of a 70/30 brass alloy, if the original gauge length (L_0) is 56 mm and the length at fracture (L_u) is 95.2 mm.

$$\begin{aligned}\text{Elongation \%} &= \frac{L_u - L_0}{L_0} \times 100 \\ &= \frac{95.2 - 56}{56} \times 100 = 70 \%\end{aligned}$$

2. The compression test

Because of the presence of submicroscopic cracks, brittle materials are often weak in tension, as tensile stress tends to propagate those cracks which are oriented perpendicular to the axis of tension. The tensile strengths they exhibit are low and usually vary from sample to sample. These same materials can nevertheless be quite strong in compression. Brittle materials are chiefly used in compression, where their strengths are much higher. A schematic diagram of a typical compression test is shown in figure 11.

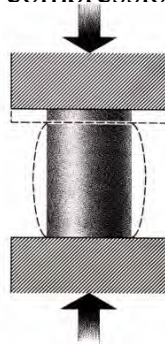


Figure 11. Compression test of ductile material.

Figure 12. shows a comparison of the compressive and tensile strengths of gray cast iron and concrete, both of which are brittle materials.

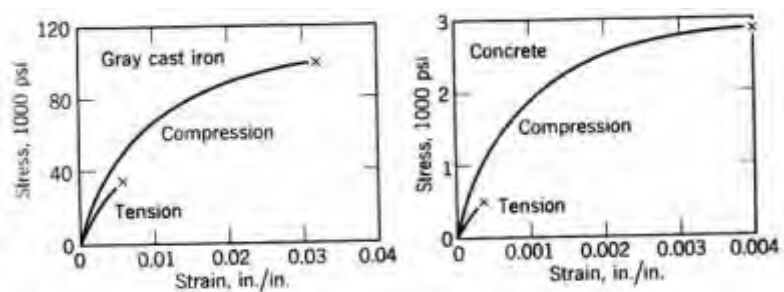


Figure 12. Tensile and compressive engineering stress-strain curves for gray cast iron and concrete.

Because the compression test increase the cross-sectional area of the sample, necking never occurs. Extremely ductile materials are seldom tested in compression because the sample is constrained by friction at the points of contact with the plants of the apparatus. This constraint gives rise to a complicated stress distribution which can only be analyzed in an approximate fashion.

3. Ductility testing

The percentage elongation, as determined by the tensile test, has already been discussed as a measure of ductility. Another way of assessing ductility is a simple bend test. There are several ways in which this test can be applied, as shown in figure 13. The test chosen will depend upon the ductility of the material and the severity of the test required.

- *Close bend test* The specimen is bent over on itself and flattened. No allowance is made for spring back, and the material is satisfactory if the test can be completed without the metal tearing or fracturing. This also applies to the following tests.
- *Angle bend test* The material is bent over a former and the nose radius of the former and the angle of bend (θ°) are fixed by specification. Again no allowance is made for spring back.
- *180 ° bend test* This is a development of the angle bend test using a flat former as shown. Only the nose radius of the former is specified.

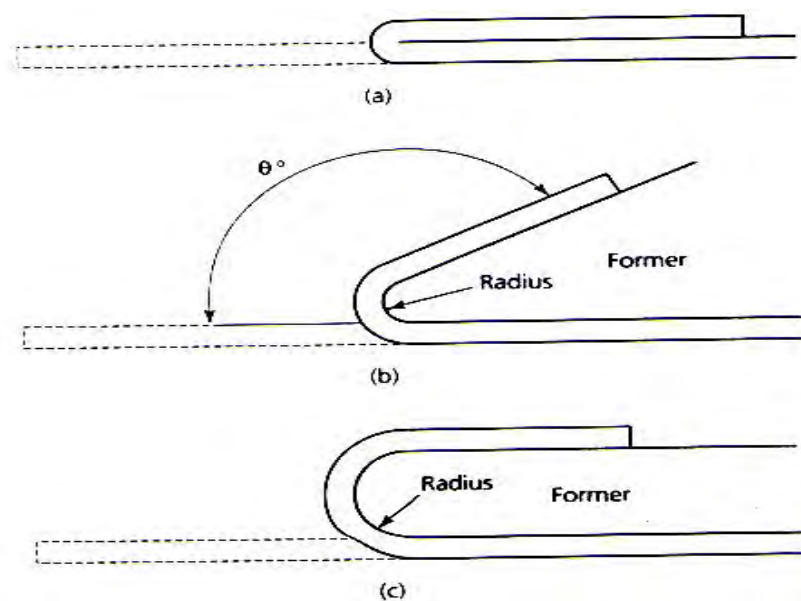


Figure 13. Bend tests: (a) close bend; (b) angle bend; (c) 180 ° bend.

4. Impact testing (toughness testing)

Impact tests consist of striking a suitable specimen with a controlled blow and measuring the energy absorbed in bending or breaking the specimen. The energy value indicates the toughness of the material under test.

Figure 14 shows a typical impact testing machine which has a hammer that is suspended like a pendulum, a vice for holding the specimen in the correct position relative to the hammer and a dial for indicating the energy absorbed in carrying out the test in joules (J).

When the heavy pendulum, released from a known height, strikes and breaks the sample before it continues its upward swing. From knowledge of the mass of the pendulum and the difference between the initial and final heights, the energy absorbed in fracture can be calculated, as shown in figure 15 the schematic drawing of the impact test machine.

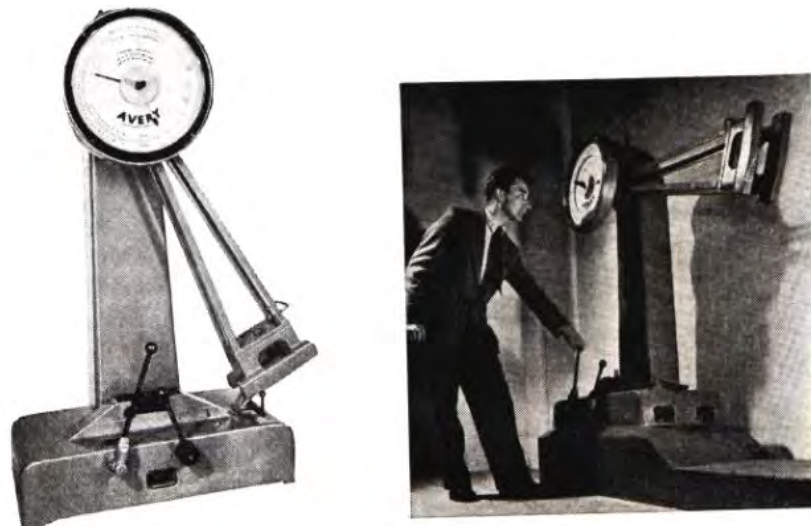


Figure 14. Typical impact testing machine.

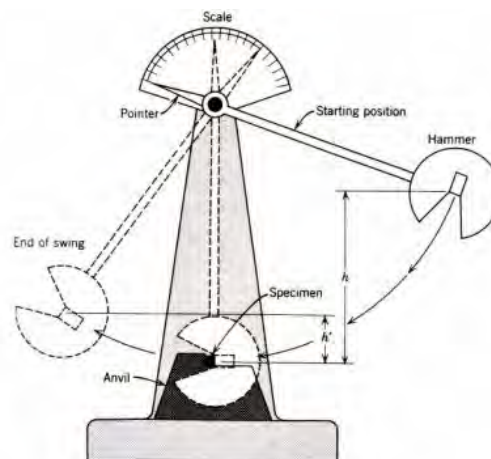


Figure 15. Schematic drawing of standard impact-testing apparatus.

Figure 16 shows how a piece of high carbon steel rod will bend when in the annealed condition, after hardening and lightly tempering, the same piece of steel will fracture when hit with a different hammer.

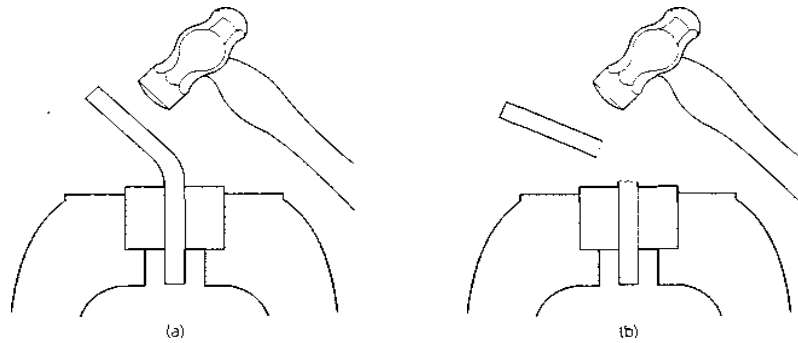


Figure 16. Impact loading: (a) a rod of high-carbon (1.0%) steel in the annealed (soft) condition will bend struck with a hammer (UTS 925 MPa); (b) after hardening and lightly tempering, the same piece steel will fracture when hit with a hammer despite its UTS having increased to 1285 MPa.

There are several types of the impact tests and the most famous type is the Izod test.

In the Izod test, a 10mm square, notched specimen is used, it is preferred to use a specimen that have a more than one or two and even three notched in the same specimen. The striker of the pendulum hits the specimen with a kinetic energy of 162.72 J at a velocity of 3.8m/s. Figure 17 shows details of the specimen and the manner in which it is supported.

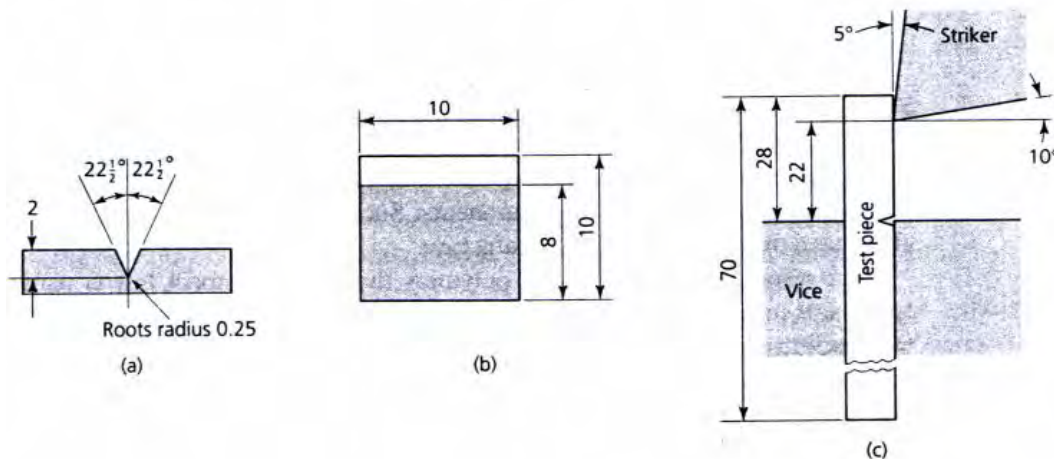


Figure 17. Izod test (a/I dimensions in millimeters); (a) detail of notch; (b) section of test piece (at notch); (c) position of strike.

Since test use a notched specimen, useful information can be obtained regarding the resistance of the material to the spread of a crack which may originate from a point of stress concentration such as sharp comers, undercuts, sudden changes in section, and machining

marks in stressed components. Such points of stress concentration should be eliminated during design and manufacture.

A second type of impact test is the Charpy test. While in the Izod test the specimen is supported as a cantilever, but in the Charpy test it is supported as a beam. It is struck with a kinetic energy of 298.3 J at a velocity of 5m/s. The Charpy impact test is usually use for testing the toughness of polymers. Figure 18 shows details of the Charpy tes: manner in which it is supported.

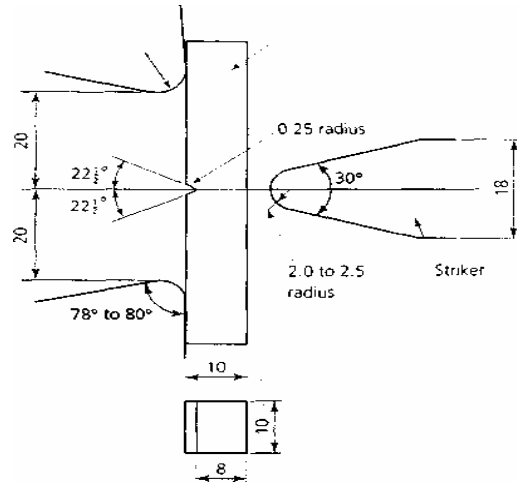


Figure 18. Charpy test (all dimensions in millimeters).

The effects of temperature on the materials mechanical properties:

The temperature of the specimen at the time of making the test also has an important influence on the test results. Figure 19 hows the embrittlement of low-carbon steels at refrigerated temperatures, and hence their unsuitability for use in refrigeration plant and space vehicles.

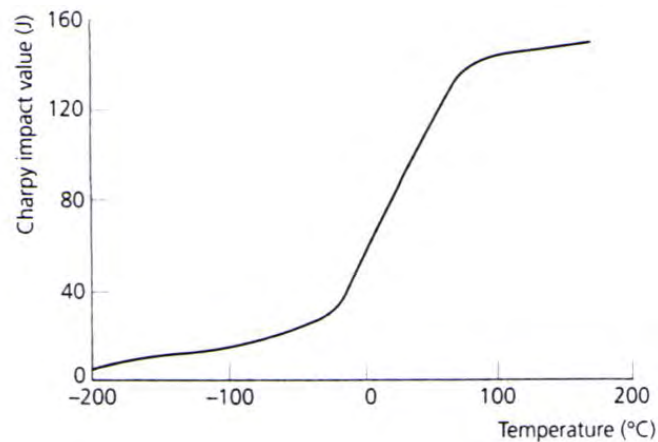


Figure 19. Effect of test temperatures on toughness.

The impact test is also useful as a production tool in comparing manufactured materials with others which have proved satisfactory in service. Steels, like most other BCC metals and alloys, absorb more energy when they fracture in a ductile fashion rather than in a brittle fashion. On this account the impact test is often used to assess the temperature of the transition from the ductile to brittle state which occurs as the temperature is lowered. The transition temperature is also dependent on the shape of the notch in the specimen. For identical materials, the sharper the notch, the higher the apparent transition temperature. The results of impact tests for several materials are shown in figure 20.

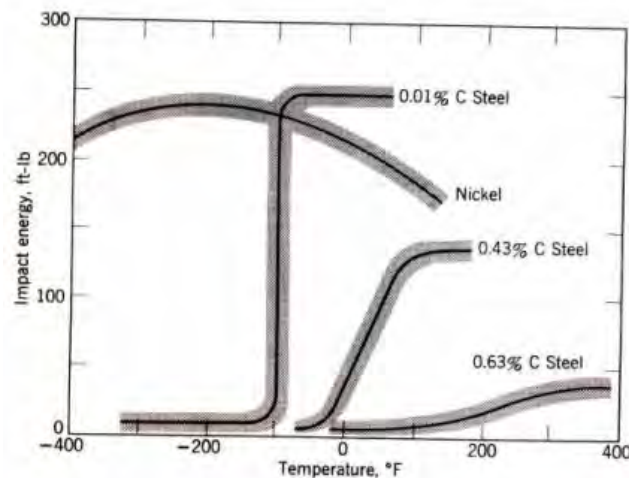


Figure 20. Impact test results for several alloys over a range of testing temperatures.

5. Creep test

Even at constant stress, materials continue to deform for an indefinite period of time. This time – dependent deformation is called creep. At temperatures less than 40 percent of the absolute melting point, the extent of creep is negligible, but at temperatures higher than this it becomes increasingly important. It is for this reason that the creep test is commonly thought of as a high-temperature test.

The majority of creep testing is conducted in the tensile mode, and the type of test-piece used is similar to the normal tensile test-piece. Most creep testing is carried out under constant-load conditions and utilizes dead weights acting through a simple lever system. In the creep testing an extensometer readings are noted at regular time intervals until the required amount of data has been obtained, or until the test-piece fractures, depending on whether the object of the test is to determine the creep rate or to determine the total creep strain.

One of the difficulties in creep testing is that a single test may take a very long time to complete (10000 hours is 417 days), and there are

serious difficulties in attempting to extrapolate from the results of comparatively short-term tests to assess the probable behavior of a material over a 10 or 20 year period of service.

Modern creep-testing laboratories may contain several hundred creep-testing machines in continuous use.

Also creep is sensitive to both the applied load and the testing temperature, as shown in figure 21: increasing stress raises the level of the creep curve, and increasing temperature, which accelerates recovery processes, increase the creep rate.

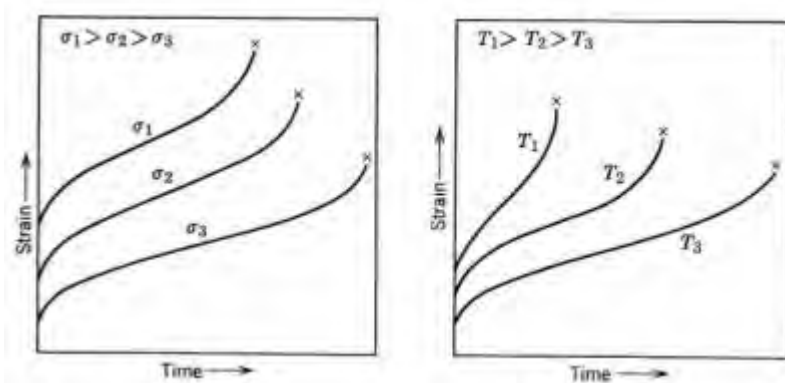


Figure 21. The effects of stress and temperature on creep behavior.

6. Hardness testing

Hardness has already been defined as the resistance of a material to indentation or abrasion by another hard body (good hardness generally means that the material is resistant to scratching and wear) . It is by indentation that most hardness tests are performed. A hard indenter is pressed into the specimen by a standard load, and the magnitude of the indentation (either area or depth) is taken as a measure of hardness.

Hardness tests are commonly used for assessing material properties because they are quick and convenient. However, a variety of testing methods is appropriate due to differences in hardness among different materials. The most well known hardness tests are Brinell and Rockwell.

1. The Brinell hardness test

In this test, hardness is measured by pressing a hard steel ball into the surface of the test piece, using a known load. It is important to choose the combination of load and ball size carefully so that the indentation is free from distortion and suitable for measurement. The relationship of the Brinell hardness [H_B] which is between load P (kg), the diameter D (mm) of the hardened ball indenter and the diameter d (mm) of the indentation on the surface is given by the expression:

$$H_B = \frac{\text{Load (Kg)}}{\text{Area of curved surface of indentation}}$$

$$H_B = \frac{P(\text{Kg})}{\frac{1}{2}\pi \times D[D - \sqrt{D^2 - d^2}](\text{mm}^2)}$$

For different materials, the ratio $\frac{P}{D^2}$ has been standardized in order to obtain accurate and comparative results such as :

$$K = \frac{P}{D^2}$$

Where K is a constant; typical values of K are:

Ferrous metals	$K = 30$
Copper and copper alloys	$K = 10$
Aluminum and aluminum alloys	$K = 5$
Lead, tin and white-bearing metals	$K = 1$

Figure 22 shows how the Brinell hardness value is determined. The diameter of the indentation is measured in two directions at right angles and the average taken. The diameter is measured either by using a microscope scale, or by a projection screen with micrometer adjustment.

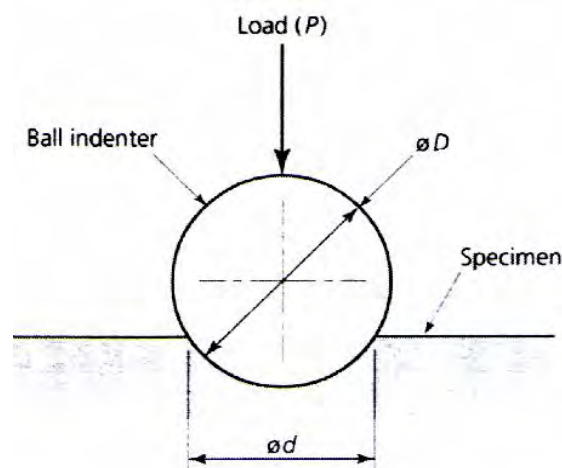


Figure 22. Principle of the Brinell hardness test.

To ensure consistent results, the following precautions should be observed.

- The thickness of the specimen should be at least seven times the depth of the indentation to allow unrestricted plastic flow below the indenter.
- The edge of the indentation should be at least three times the diameter of the indentation from the edge of the test piece.
- The test is unsuitable for materials whose hardness exceeds 500 H_B, as the ball indenter tends to flatten.

There are a definite relationship between strength and hardness so it is possible to measure the tensile strength from the hardness test.

2. *The Vickers hardness test*

This test is preferable to the Brinell test where hard materials are concerned, as it uses a diamond indenter. (Diamond is the hardest material known - approximately 6000 H_B.) The diamond indenter is in the form of a square-based pyramid with an angle of 136° between opposite faces.

Since only one type of indenter is used the load has to be varied for different hardness ranges. Standard loads are 5, 10, 20, 30, 50 and 100 kg. It is necessary to state the load when specifying a Vickers hardness number. For example, if the hardness number is found to be 200 when using a 50 kg load, then the hardness number is written as H_V (50) = 200.

Figure 23 shows the measuring screen for determining the distance across the corners of the indentation. The screen can be rotated so that two readings at right angles can be taken and the average is used to determine the hardness number (H_D). This is calculated by dividing the load by the projected area of the indentation:

$$H_v = \frac{\text{Load (Kg)}}{\text{Surface area of indentation (mm}^2\text{)}}$$

$$H_v = \frac{P(\text{Kg})}{[d^2/2 \sin \frac{1}{2}(136^\circ)](\text{mm}^2)}$$

$$= \frac{2P \sin 68^\circ}{d^2} = 1.854 \frac{P}{d^2}$$

where P is the load in Kg and d (mm) is the diagonal of the impression made by the indenter made by the diamond.

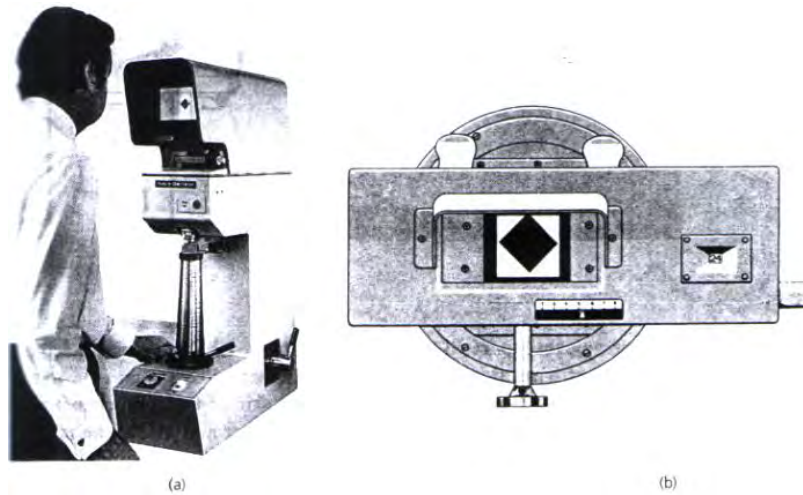


Figure 23. The Vickers hardness test method: (a) universal hardness-testing machine; (b) measuring screen showing magnified of Vickers impression.

3. The Rockwell hardness test

Although not as reliable as the Brinell and Vickers hardness tests for laboratory purposes, the Rockwell test is widely used in industry as it is quick, simple and direct reading. Universal electronic hardness testing machines are now widely used which, at the turn of a switch, can provide either Brinell, Vickers or Rockwell tests and show the hardness number as a digital readout automatically. They also give a "hard copy" printout of the test result together together with the test conditions and date.

In principle the Rockwell hardness test compares the difference in depth of penetration of the indenter when using forces of two different values. That is, a minor force is first applied (to take up the backlash and pierce the skin of the component) and the scale are set to read zero. Then a major force is applied over and above the minor force and the increased depth of penetration is shown on the scales of the machine as a direct reading of hardness without the need for calculation or conversion tables. Figure 24 shows a typical Rockwell hardness testing machine.

The standard Rockwell test can not be used for very thin sheet and foils and for these the Rockwell superficial hardness test is used.

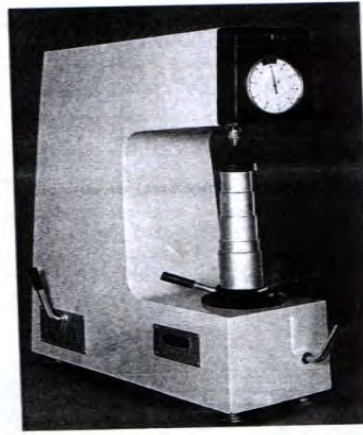


Figure 24. The Rockwell hardness test.

4. Shore Scleroscope

The test piece must be small enough to mount in the testing machine, and hardness is measured as a function of indentation. However, the scleroscope is not like other types of hardness tests based their measure on the ratio of applied load divided by the resulting impression are [like Brinell and Vicker well] or by the depth of impression [like Rock well].

The scleroscope is an instrument that measures the rebound height of a hammer dropped from a certain distance above the surface of the material to be tested. The hammer consist of a weight with diamond indenter attached to it. The scleroscope therefore measures the mechanical energy absorbed by the material when the indenters strikes the surface. The energy absorbed gives an indication of resistance to penetration, which matches our definition of hardness. As shown in figure 25.

The primary use of the scleroscope seems to be in measuring the hardness of large parts of steel, large rolls, casting and gears. And since the scleroscope can be carried to the work piece, it is useful for testing large surfaces and other components which could not easily be placed on the testing tables of any other testing machines.

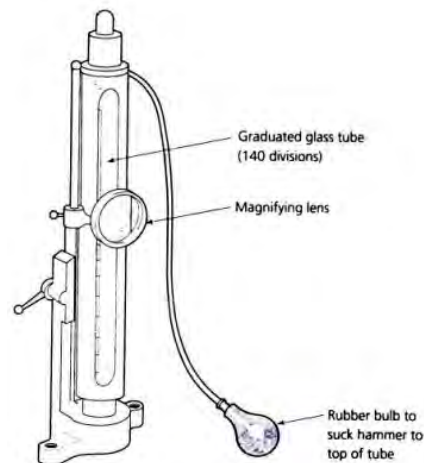
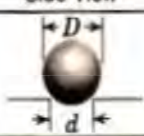

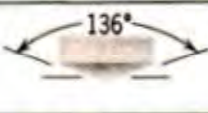









Figure 25. Shore scleroscope.

The table below shows the different in the ways of measuring the hardness numbers for methods we mentioned above.

Table 1. Hardness tests.

Test	Indenter	Shape of Indentation Side View	Top View	Load	Formula for Hardness Number	
Brinell	10 mm sphere of steel or tungsten carbide			P	$BHN = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})}$	
Vickers	Diamond pyramid			P	$VHN = 1.72P/d_1^2$	
Rockwell						
A } C } D }	Diamond cone			60 kg	$R_A =$	} 100-500t
				150 kg	$R_C =$	
				100 kg	$R_D =$	
B } F } G }	$\frac{1}{16}$ in. diameter steel sphere			100 kg	$R_B =$	} 130-500t
				60 kg	$R_F =$	
				150 kg	$R_G =$	
E	$\frac{1}{8}$ in. diameter steel sphere			100 kg	$R_E =$	

Engineering Materials

5

Surface Hardening of Steel

Introduction:

The service conditions of many steel components such as cams and gears, make it necessary for them to possess both hard, wear-resistant surfaces and, at the same time, tough, shock-resistant cores.

In plain carbon steels these two different sets of properties exist only in alloys of different carbon content. A low-carbon steel, containing approximately 0-1% carbon, will be tough, whilst a high-carbon steel of 0-9% or more carbon will possess adequate hardness when suitably heat-treated.

The situation can best be met by employing a low-carbon steel with suitable core properties and then causing either carbon or nitrogen to penetrate to a regulated depth into the surface skin; as in the principal surface-hardening processes of carburising and nitriding.

Alternatively, a steel of medium carbon content and in the normalised condition can be used, local hardness at the surface then being introduced by one or other of the name-hardening processes.

In the first case the hardenable material is localised, whilst in the second case it is the heat-treatment itself which is localised.

There are four main types of the surface hardening which are :-

1. *Case hardening*
2. *Nitriding*
3. *Flam hardening*
4. *Induction hardening*

The first two types include a change in the chemical structure of the surface while the other types include a change in the micro constituents as a result for the positional heat treatment.

1. Case hardening

Is one of the most used for producing a hard surface on a ductile steel. It involves the introduction of additional carbon into the surface of mild steel, effectively producing a composite material consisting of low carbon steel with a thin case, about 0.5 – 0.7 mm in thickness, of high carbon steel, this was the principle of case-hardening that have been used for centuries in the conversion of mild or wrought iron to steel by the cementation process.

The case-hardening consists in surrounding the component with suitable carbon material and heating it to above its upper critical temperature for long enough to produce a carbon enriched layer of sufficient depth.

Solid, liquid and gaseous carburizing media are used. The nature and scope of the work involved will govern which media is best to employ.

The case-hardening process has two distinct steps, as shown in figure 1:

- Carburising (the additional of carbon)
- Heat treatment (hardening and core refinement)

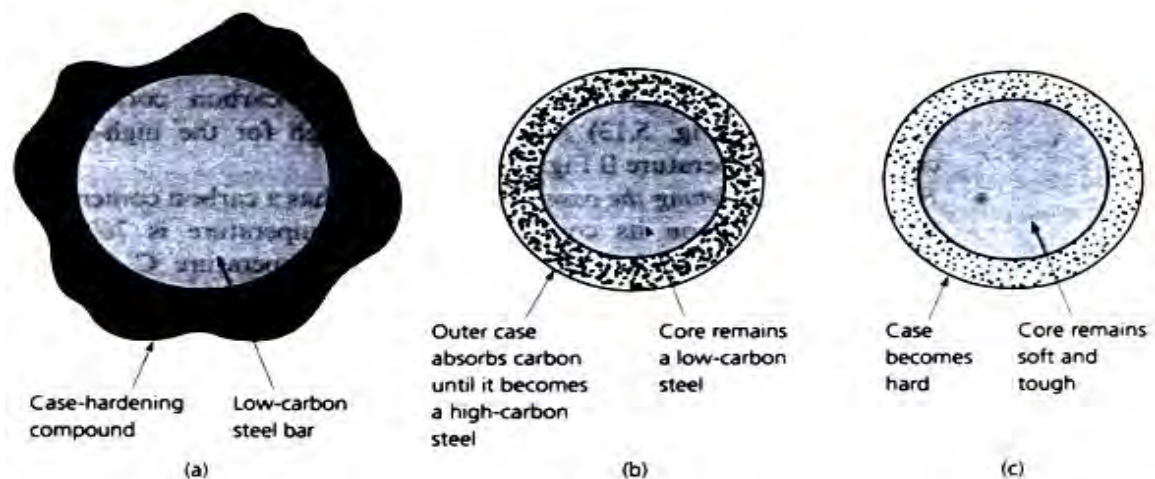


Figure 1. Case hardening : (a) carburising, (b) after carburising, (c) after quenching component.

1. Carburising

Carburizing makes use of the fact that low carbon steel absorb carbon when heated to the austenitic condition various carbonaceous materials are used in the carburizing process as follows:-

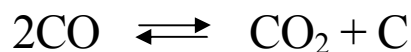
1.1 Carburising in solid media

"Pack-carburising", as it is usually called, involves packing the components into cast-iron or steel boxes along with the carburizing material so that a space of approximately 50 mm exists between the components. The lids are then luted on to the boxes, which are slowly

heated to the carburizing temperature for between 900 and 950° C. they are maintained at this temperature for up to five hours, according to depth of case required.

Carburising media vary in composition, but consist essentially of some carbonaceous material, such as wood or bone charcoal or charred leathers together with an energiser which may account for up to 40% of the total composition. This energiser is usually a mixture of sodium carbonate ("soda ash") and barium carbonate, and its purpose is to accelerate the solution of carbon by the surface layer of the steel.

It is thought that carburisation proceeds by dissociation of carbon monoxide which will be present in the hot box. When the gas comes into contact with the hot steel it dissociates thus:



The atomic carbon deposited at the surface of the steel dissolves easily in the metal. In this method of carburizing the thickness of the surface is between 0.05 – 1.55 mm.

If it is necessary to prevent any areas of the component from being carburised, this can be achieved by electro-plating these areas with copper to a thickness of 0.075-0.10 mm; carbon being insoluble in solid copper at the carburising temperature.

When carburising is complete the components are quenched or cooled slowly in the box, according to the nature of the subsequent heat-treatment to be applied.

1.2 Carburising in a liquid bath (Cyaniding)

Liquid-carburising is carried out in baths containing from 20 to 50% sodium cyanide, together with up to 40% sodium carbonate and varying amounts of sodium chloride.

This cyanide-rich mixture is heated in pots to a temperature of 870-950° C, and the work, which is contained in wire baskets, is immersed for periods varying from about five minutes up to one hour, depending upon the depth of case required.

One of the main advantages of cyanide-hardening is that pyrometric control is so much more satisfactory with a liquid bath. Moreover, after treatment the basket of work can be quenched. This not only produces the necessary hardness but also gives a clean surface to the components.

The process is particularly useful in obtaining shallow cases of 0.1 – 0.25 mm.

Dissociation of the carbon monoxide at the steel surface then takes place with the same result as in pack-carburising. The nitrogen, in atomic form, also dissolves in the surface and produces an increase in hardness by the formation of nitrides as it does in the nitriding process.

Cyanides are, of course, extremely poisonous, and every precaution should be taken to avoid inhaling the fumes from a pot. Every pot should be fitted with an efficient fume-extracting hood. Likewise the salts should in no circumstances be allowed to come into contact with an open wound. Needless to say, the consumption of food by operators whilst working in the shop containing the cyanide pots should be *Absolutely forbidden*.

1.3 Carburising by gaseous media

Gas-carburising is carried out in both batch-type and continuous furnaces. The components are heated at about 900° C for three or four hours in an atmosphere containing gases which will deposit carbon atoms at the surface of the components. The most important of these gases are the hydrocarbons methane CH_4 , and propane, C_3H_8 .

They should be of high purity in order to avoid the deposit of oily soot which impedes carburising. To facilitate better gas circulation and hence, greater uniformity of treatment the hydrocarbon is mixed with a "carrier" gas. This is generally an "endothermic" type of atmosphere made in a generator and consisting of a mixture containing mainly nitrogen, hydrogen and carbon monoxide.

The relative proportions of hydrocarbon and carrier are adjusted to give the desired carburizing rate. Thus, the concentration gradient of carbon in the surface can be "flattened" by prolonged treatment in a less rich carburising atmosphere. Control of this type is possible only with gaseous media.

Gas-carburising is becoming increasingly popular, particularly for the mass production of thin cases. Not only is it a neater and cleaner process but the necessary plant is more compact for a given output.

Moreover, the carbon of the surface layers can be controlled more accurately and easily with thickness of about 0.25 – 1.0 mm.

2. Heat treatment after Carburising

If carburising has been correctly carried out, the core will still be of low carbon content (0.1 – 0.2% carbon), whilst the case should have a maximum carbon content of 0.83% carbon (the eutectoid composition), as shown in figure 2.

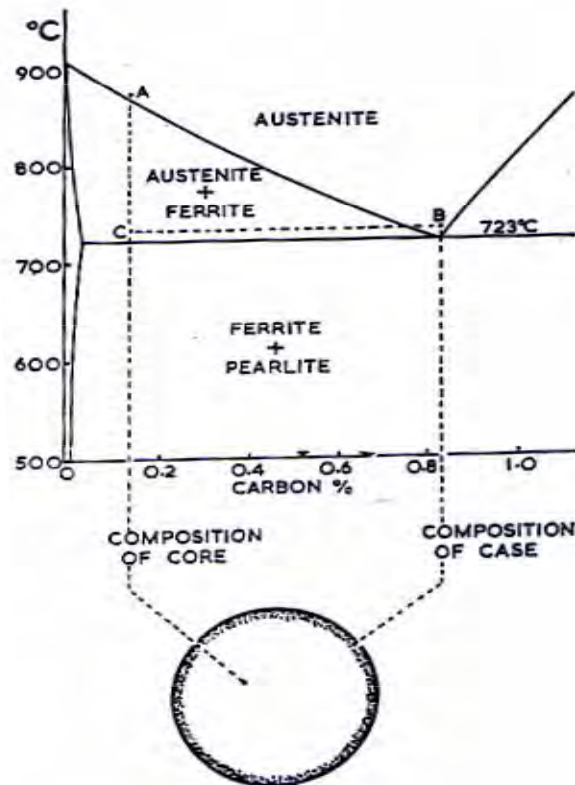


Figure 2. Heat-treatment After Carburising.

A Indicates the temperature of treatment for the core, and *B* the temperature of treatment for the case.

Considerable grain growth occurs in the material during a carburizing treatment, therefore a three stage of heat treatment must be given to the carburized parts to produce the desired final properties. This heat treatment involves:

2.1 Refining the core

The component is first heat-treated with the object of refining the grain of the core, and consequently toughening it. This is effected by heating it to just above its upper critical temperature (about 870° C for the core) when the coarse ferrite-pearlite structure will be replaced by refined austenite crystals. The component is then water-quenched, so that a fine ferrite-martensite structure is obtained.

The core-refining temperature of 870° C is, however, still high above the upper critical temperature for the case, so that, at the quenching temperature, the case may consist of large austenite grains. On

quenching these will result in the formation of coarse brittle martensite. Further treatment of the case is therefore necessary.

2.2 Refining the case

The component is now heated to about 760° C, so that the coarse martensite of the case changes to fine-grained austenite. Quenching then gives a fine-grained martensite in the case.

At the same time the martensite produced in the core by the initial quench will be tempered somewhat, and much will be reconverted into fine-grained austenite embedded in the ferrite matrix (point C in Figure.2). The second quench will produce a structure in the core consisting of martensite particles embedded in a matrix of ferrite grains surrounded by bainite. The amount of martensite in the core is reduced if the component is heated quickly through the range 650-760° C and then quenched without soaking. This produces a core structure consisting largely of ferrite and bainite, and having increased toughness and shock-resistance.

2.3 Tempering

The component is tempered at about 200 – 220 ° C to relieve any quenching strains present in the case.

2. Nitriding

The process is used to put a hard, wear-resistant (مقاومة البلى) coating on components made from special alloy steels, for example, drill bushes. The alloy steels used for this process contain either 1.0% aluminium, or traces of molybdenum, chromium and vanadium. Nitrogen gas is absorbed into the surface of the metal to form very hard nitrides. The process consists of heating the components in ammonia gas at between 500 and 600 °C for upwards of 40 hours.

At this temperature the ammonia gas breaks down and the atomic nitrogen is readily absorbed into the surface of the steel. The case is applied to the finished component. No subsequent grinding is possible since the case is only a few micrometres thick. However, this is no disadvantage since the process does not affect the surface finish of the component and the process temperature is too low to cause distortion. Some of the advantages of nitriding are:

- Cracking and distortion are eliminated since the processing

temperature is relatively low and there is no subsequent quenching.

- Surface hardnesses as high as 1150 H_D are obtainable with 'Nitralloy' steels.
- Corrosion resistance of the steel is improved.
- The treated components retain their hardness up to 500 °C compared with the 220 °C for case-hardened plain carbon and low-alloy steels.
- Resistance to fatigue is good.
- The process is cheap when large number of components are to be treated.

As disadvantage of nitriding is more expensive than that with case-hardening, so that the process is economical only when large number of components are to be treated.

Carbonitriding. This is a surface-hardening process which makes use of a mixture of carburising gases and ammonia. It is sometimes known as "**dry cyaniding**" — a reference to the fact that a mixed carbide-nitride case is produced as in the ordinary liquid cyanide process. The relative proportions of carbon and nitrogen in the case can be varied by controlling the ratio of ammonia to hydrocarbons in the treatment atmosphere.

3. Flame hardening

Localised surface hardening can also be achieved in medium- and high-carbon steels and some cast irons by rapid local heating and quenching. Figure 3 shows the principle of flame hardening. A carriage moves over the work piece so that the surface is rapidly heated by an oxy-acetylene or an oxy-propane flame. The same carriage carries the water-quenching spray. Thus the surface of the work piece is heated and quenched before its core can rise to the hardening temperature. This process is often used for hardening the slideways of machine tools, such as gears, spindles and pins, that are confidently treated by this process, since they can be spun between centers.

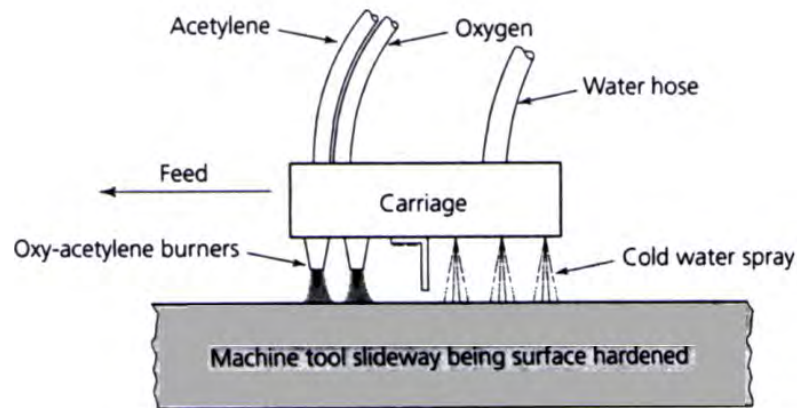


Figure 3. *Surface hardening with flame hardening (Shorter process).*

4. Induction hardening

These processes are similar in principle to flame-hardening, except that the component is held stationary- whilst the whole of its surface is heated simultaneously by electro-magnetic induction, as shown in figure 4. The component is surrounded by an inductor block through which a high-frequency current in the region of 2000 Hz , passes. This raises the temperature of the surface layer to above its upper critical in a few seconds. The surface is then quenched by pressure jets of water which pass through holes in the inductor block.

Thus, as in flame-hardening, the induction processes make use of the existing carbon content (which must be above 0-4%), whilst in both case-hardening and nitriding an alteration in the composition of the surges layer of the steel takes place.

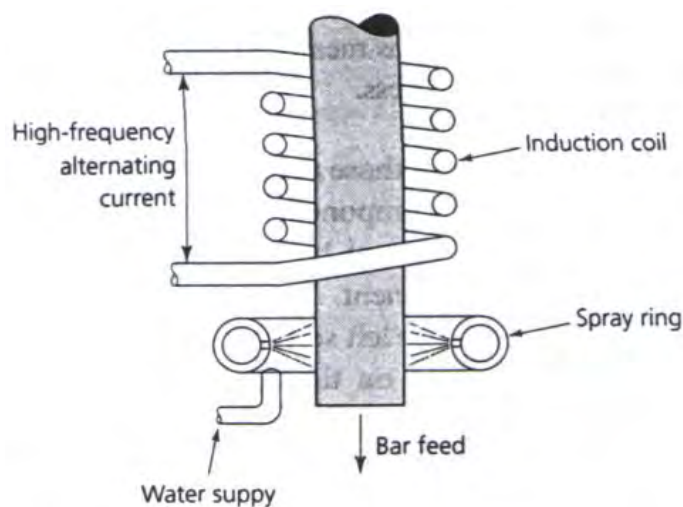


Figure 4. *Surface hardening with induction hardening.*

Engineering Materials

6

Phase Equilibrium Diagrams

Phase equilibrium diagram is a graphic relationship between temperature and weight ratios of elements and alloys contribute to the built of the diagram.

Where *Phase* is a uniform part of an alloy, having a certain chemical composition and structure, and which is separated from other alloy constituents by a phase boundary.

For example the salt – water solution have a four possible phases:

- Water vapor (steam)
- Liquid salt solution (sodium chloride in water)
- Crystals of water (ice)
- Crystals of salt (sodium chloride)

Alloying systems :

Alloy is a metal composing of a mixture of elements. Most of alloys are composed of a base metal with small amounts of additives or alloying elements. The typical examples of alloys are steel/cast iron (iron base alloys), bronze/brass (copper base alloys), aluminum alloys, nickel base alloys, magnesium base alloys, titanium alloys.

There are many types of alloying systems which they are:

- Binary system

It means that alloying have two metals only.

- Ternary system

It means that alloying have three metals only.

- Multi system

It means that alloying have three and more than that metals.

The constituent components of most commercially available binary alloys are completely soluble in each other in the liquid (molten) state and, in general, do not form intermetallic compounds. (The exceptions being some bearing metals.) However, upon cooling into the solid state, binary alloys can be classified into the following types.

- ***Simple eutectic type*** The two components are soluble in each other in the liquid state but are completely insoluble in each other in the solid state.
- ***Solid solution type*** The two components are completely soluble in each other both in the liquid state and in the solid state.
- ***Combination type*** The two components are completely soluble in the liquid state, but are only partially soluble in each other in the solid state. Thus this type of alloy combines some of the characteristics of both the previous types, hence the name ‘combination type’ phase equilibrium diagram.

Let's now consider these three types of binary alloy systems and their phase equilibrium diagrams in greater detail.

1) Phase equilibrium diagrams (Eutectic type):

In general case, consider for studying a two components presents which are referred to as metal A and metal B, with the phase diagram as shown in figure 1.

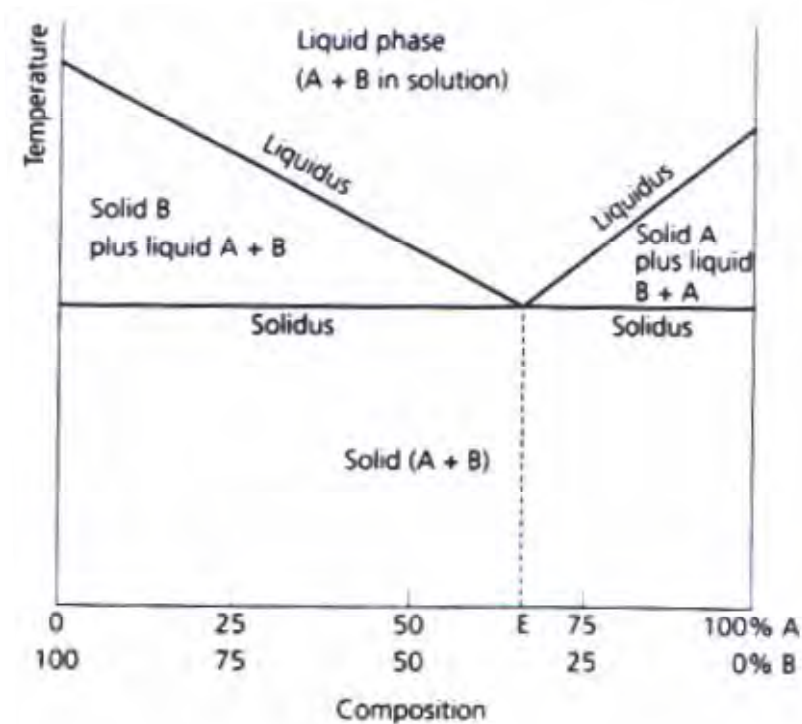


Figure 1. Phase equilibrium diagram (eutectic type).

Although they are mutually soluble in the liquid state, both components retain their individual identities of crystals of A and crystals of B in the solid state. If you refer to figure 1, you can see that the line joining the points where solidification begins is referred to as the *liquidus* and that the line joining the points where solidification is complete is referred to as the *solidus*.

This type of equilibrium diagram gets its name from the fact that at one particular composition (E), the temperature at which solidification commences is a minimum for the alloying elements present. With this composition the liquidus and the solidus coincide at the same temperature, thus the liquid changes into a solid with both A crystals and B crystals forming instantaneously at the same temperature. This point on the diagram is called the *eutectic*, the temperature at which it occurs is the *eutectic temperature*, and the composition is the *eutectic composition*.

In practice, few metal alloys from simple eutectic type phase diagrams. It is identical with this type of phase diagram is produced for a salt (sodium chloride) and water solution, it is total solubility of the salt in water in the liquid state and total insolubility (crystals of ice and separate crystals of salt) in the solid state. As an example of eutectic are carbon steels.

2) *Phase equilibrium diagrams (Solid solution type):*

Solid solution is a phase, where two or more elements are completely soluble in each other.

Depending on the ratio of the solvent (matrix) metal atom size and solute element atom size, two types of solid solutions may be formed: substitution or interstitial.

Substitution solid solution

If the atoms of the solvent metal and solute element are of similar sizes (not more, than 15% difference), they form **substitution solid solution**, where part of the solvent atoms are substituted by atoms of the alloying element as shown in figure 2.

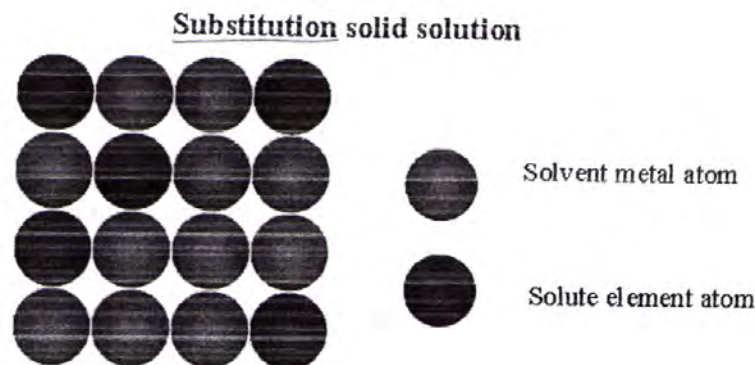


Figure 2. Substitution solid solution.

Interstitial solid solution

If the atoms of the alloying elements are considerably smaller, than the atoms of the matrix metal, **interstitial solid solution** forms, where the matrix solute atoms are located in the spaces between large solvent atoms as shown in figure 3.

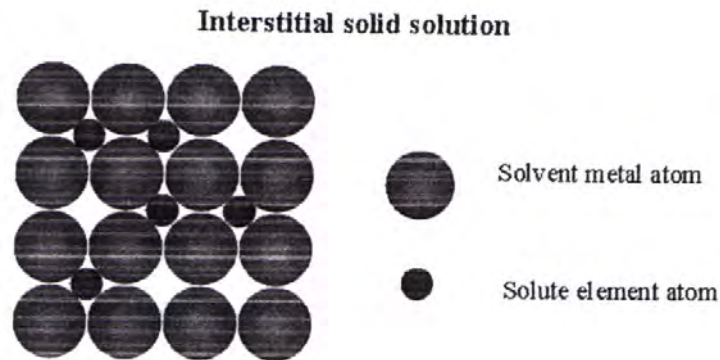


Figure 3. Interstitial solid solution.

When the solubility of a solute element in interstitial solution is exceeded, a phase of intermediate compound forms. These compounds (WC, Fe₃C etc.) play important role in strengthening steels and other alloys.

Some substitution solid solutions may form ordered phase where ratio between concentration of matrix atoms and concentration of alloying atoms is close to simple numbers like AuCu₃ and AuCu.

Solid solution formation usually causes increase of electrical resistance and mechanical strength and decrease of plasticity of the alloy.

In this type as shown in figure below the line marked liquids joins the points where solidification commences, whilst the line marked solidus joins the points where solidification is complete. This time there is no eutectic composition. It has already been stated that copper and nickel are not only mutually soluble in the liquid (molten) state, they are a/so mutually soluble in the solid state and they form a substitutional solid solution. The phase equilibrium diagram for copper-nickel alloys is shown in figure 4.

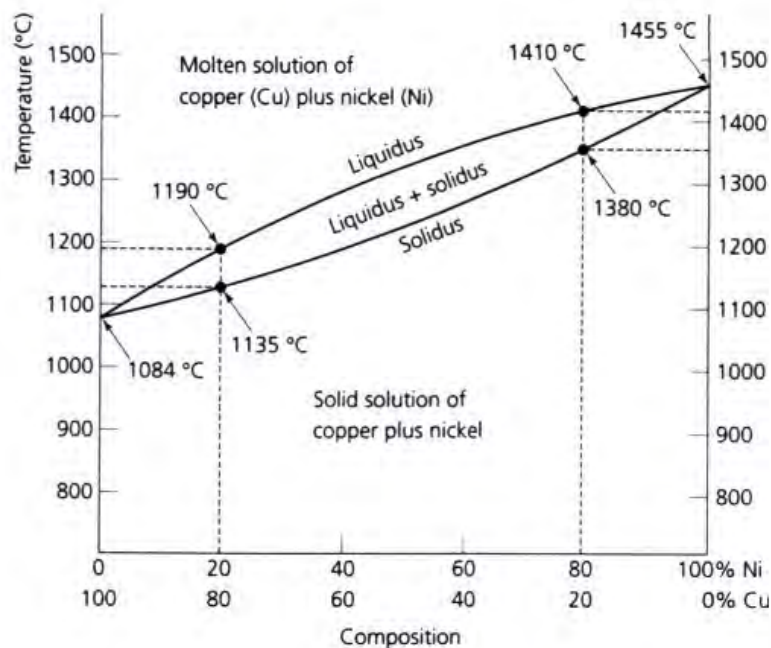


Figure 4. Copper-nickel phase equilibrium diagram.

3) Phase equilibrium diagrams (Combination type):

Many metals and non-metals are neither completely soluble in each other in the solid state nor are they completely insoluble. Therefore they form a phase equilibrium diagram of the type shown in figure 5. In this system there are two solid solutions labelled α and β . The use of the Greek letters α , β , γ , etc., in phase equilibrium diagrams may be defined, in general, as follows:

- A solid solution of one component A in an excess of another component B, such that A is the solute and B is the solvent, is referred to as solid solution α .
- A solid solution of the component B in an excess of the component A, so that B now becomes the solute and A becomes the solvent, is referred to as solid solution β .
- In a more complex alloy, any further solid solutions or intermetallic compounds which may be formed would be referred to by the subsequent letters of the Greek alphabet. That is, γ , δ , etc.

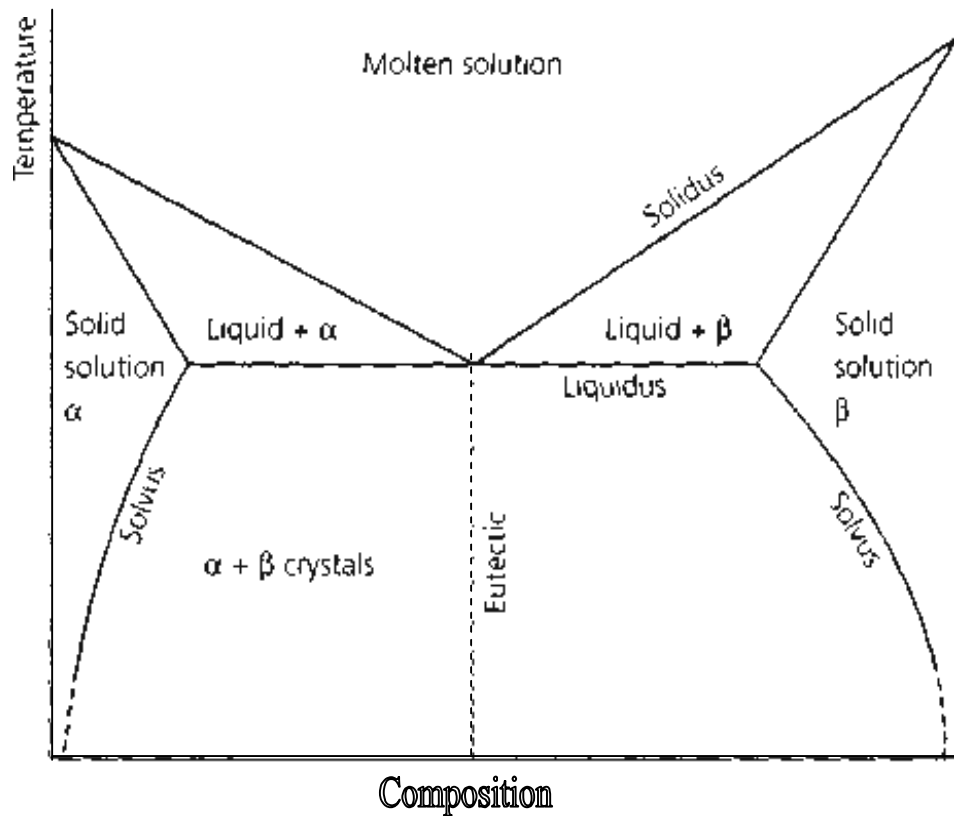


Figure 5. Combination type phase equilibrium diagram.

We will study the iron-carbon phase diagram as an example on the phase equilibrium diagram which it describes the iron-carbon system of alloys, containing up to 6.67 % carbon, discloses the phases compositions and their transformations occurring with the alloys during their cooling or heating, as shown in figure 6.

Carbon content 6.67 % corresponds to the fixed composition of the iron carbide Fe_3C .

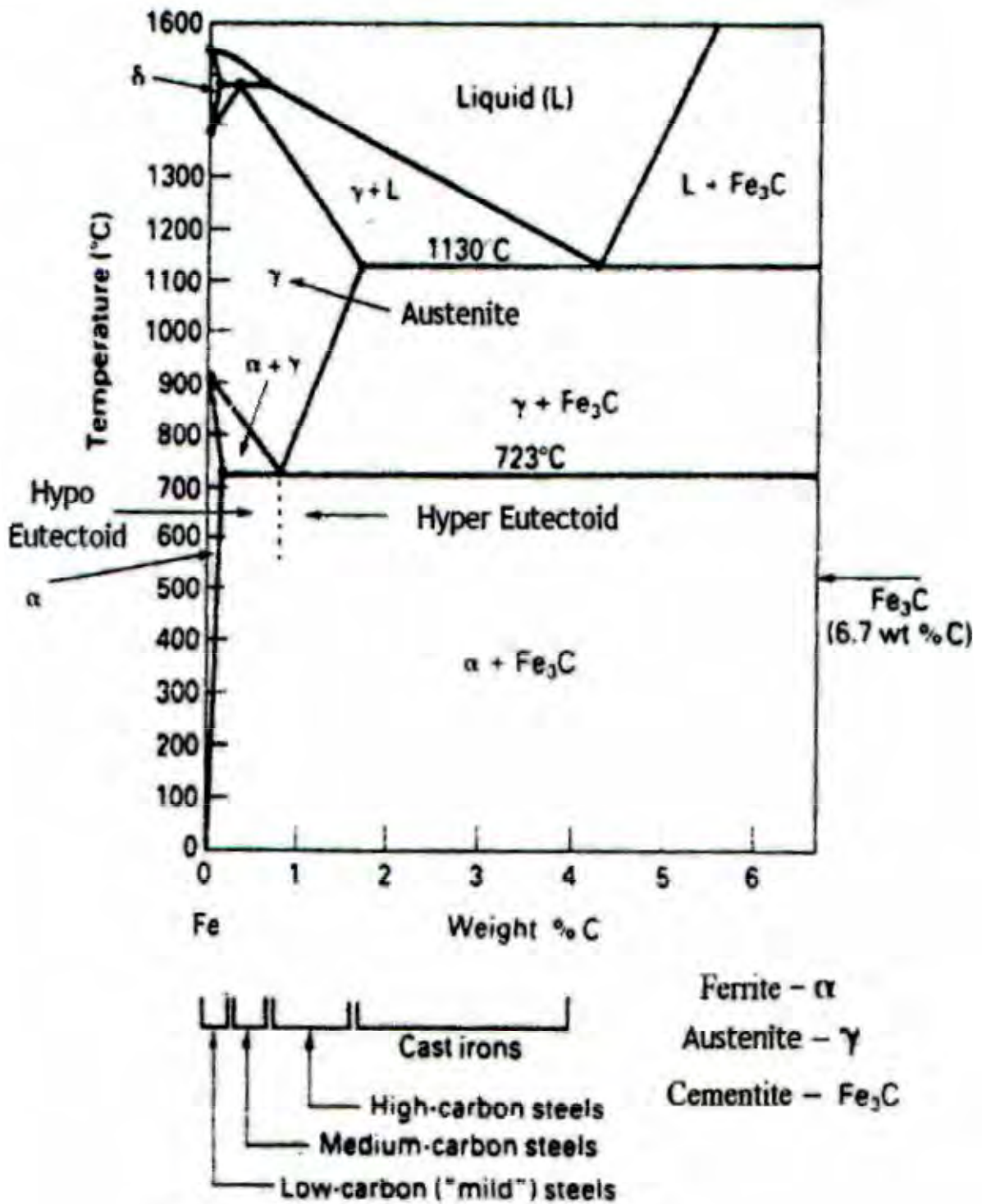


Figure 6. Iron-carbon phase diagram.

The following phases are involved in the transformation, occurring with iron-carbon alloys:

L Liquid solution of carbon in iron.

δ ferrite solid solution of carbon in iron. Maximum concentration of carbon in δ -ferrite is 0.09 % (1493°C) temperature of the peritectic transformation. The crystal structure of δ -ferrite is BCC (cubic body centered).

Austenite interstitial solid solution of carbon in γ -iron. It has FCC (cubic face centered) crystal structure, permitting high solubility of carbon up to 2.06 % at (1147°C). It does not exist below (723°C) and maximum carbon concentration at this temperature is 0.83 % .

α – ferrite solid solution of carbon in α -iron . It has BCC crystal structure and low solubility of carbon up to 0.25 % at (723°C). It exists at room temperature.

Cementite iron carbide, intermetallic compound, having fixed composition Fe_3C . It is a hard and brittle substance, influencing on the properties of steel and cast irons.

The following phase transformations occur with iron-carbon alloys:

Alloys, containing up to 0.51% of carbon, start solidification with formation of crystals of δ -ferrite. Carbon content in δ -ferrite increases up to 0.09% in course solidification, and at (1493°C) remaining liquid phase and δ -ferrite perform peritectic transformation, resulting in formation of austenite.

Alloys, containing carbon more than 0.51%, but less than 2.06%, form primary austenite crystals in the beginning of solidification and when the temperature reaches the curve ACM primary cementite starts to form.

Iron-carbon alloys, containing up to 2.06% of carbon, are called Steels.

Alloys, containing from 2.06 to 6.67% of carbon, experience eutectic transformation at (1147 °C). The eutectic concentration of carbon is 4.3% .

In practice only hypoeutectic alloys are used. These alloys (carbon content from 2.06% to 4.3%) are called cast irons. When temperature of an alloy from this range reaches 2097 °F (1147 °C), it contains primary austenite crystals and some amount of the liquid phase. The latter decomposes by eutectic mechanism to a fine mixture of austenite and cementite, called **ledeburite**.

All iron-carbon alloys (steels and cast irons) experience eutectoid transformation at (723°C), The eutectoid concentration of carbon is 0.83%.

When the temperature of an alloy reaches (723°C), austenite transforms to pearlite (fine ferrite-cementite structure, forming as a result of decomposition of austenite at slow cooling conditions).

Critical temperatures

- **Upper critical temperature (point) A_3** is the temperature, below which ferrite starts to form as a result of ejection from austenite in the hypoeutectoid alloys.
- **Upper critical temperature (point) ACM** is the temperature, below which cementite starts to form as a result of ejection from austenite in the hypereutectoid alloys.
- **Lower critical temperature (point) A_1** is the temperature of the austenite-to-pearlite eutectoid transformation. Below this temperature austenite does not exist.
- **Magnetic transformation temperature A_2** is the temperature below which α -ferrite is ferromagnetic .

Phase compositions of the iron-carbon alloys at room temperature:

- **Hypoeutectoid steels** (carbon content from 0 to 0.83%) consist of primary (proeutectoid) ferrite (according to the curve A3) and pearlite.
- **Eutectoid steel** (carbon content 0.83%) entirely consists of pearlite.
- **Hyperelltectoid steels** (carbon content from 0,83 to 2.06%) consist of primary (proeutectoid)cementite (according to the curve ACM) and pearlite.
- **Cast irons** (carbon content from 2.06% to 4.3%) consist of proeutectoid cementite CT ejected from austenite according to the curve ACM , peaiiite and transformed ledeburite (ledeburite in which austenite transformed 10 pearlite).

Engineering Materials

7

Heat treatment of carbon steel

Introduction :

Plain carbon steels and alloy steels are among the relatively few engineering materials which can be usefully heat treated in order to vary their mechanical properties. The other main group is the heat-treatable aluminium alloys. Steels can be heat treated because of the structural changes that can take place within solid iron-carbon alloys. The various heat-treatment processes appropriate to plain carbon steels are:

- Annealing.
- Normalising.
- Hardening.
- Tempering.

In all the above processes the steel is heated slowly to the appropriate temperature for its carbon content and then cooled. It is the rate of cooling which determines the ultimate structure and properties that the steel will have, providing that the initial heating has been slow enough for the steel to have reached phase equilibrium at its process temperature. Figure 1 shows the types of the ranges of carbon steels.

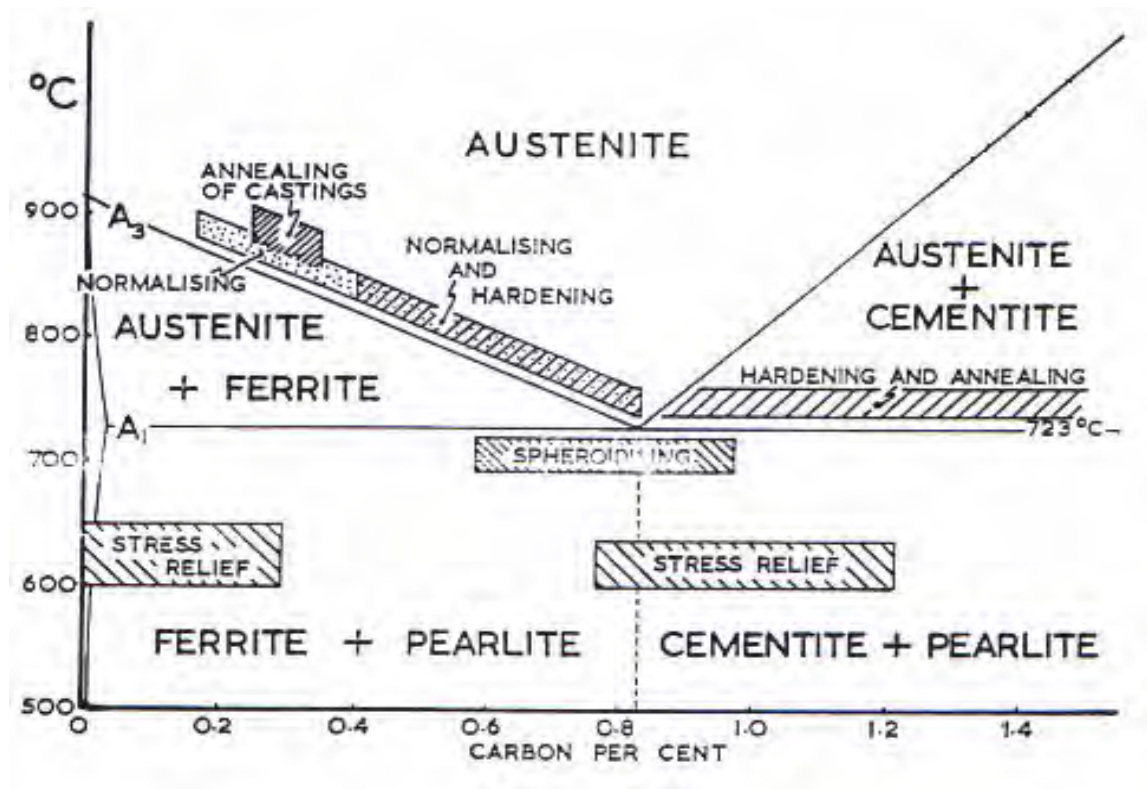


Figure 1. Heat-treatment temperature Ranges of Classes of Carbon Steels in Relation to the Equilibrium Diagram.

1. Annealing

All annealing processes are concerned with rendering steel soft and ductile so that it can be cold worked and/or machined. There are three basic annealing processes, as shown in figure 2, and these are:

- *Stress-relief annealing* at subcritical temperatures.
- *Spheroidised annealing* at subcritical temperatures.
- *Full annealing* for forgings and castings.

The process chosen depends upon the carbon content of the steel, its pretreatment processing, and its subsequent processing and use.

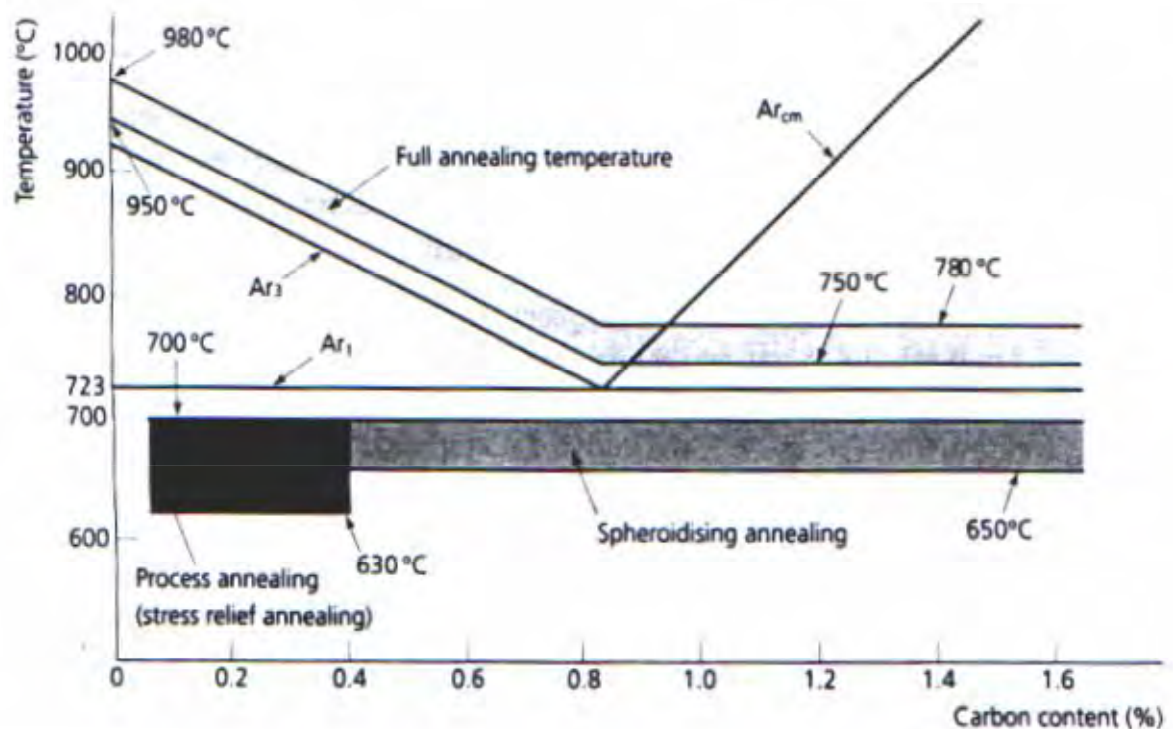


Figure 2. Annealing temperature for plain carbon steel .

a) Stress-relief annealing

It is also called 'process annealing' , 'interstage annealing' and sub-critical annealing, it is often used for softening cold worked low carbon (0.4 % carbon content) steel or mild steel . To fully anneal such a steel would involve heating to a temperature of more than 900°C, with consequent high cost. In a mild steel ferrite makes up about 90 % of the structure, and the recrystallisation temperature of cold worked ferrite is only about 500°C. annealing a cold worked mild steel in the temperature range 550 – 600 °C will result in complete recrystallisation of ferrite, although the cold worked pearlite will be largely unaffected.

Frequently, however, we must apply a considerable amount of cold-work to mild steels, as, for example, in the drawing of wire. Stress-relief annealing then becomes necessary to soften the metal so that further drawing operations can be carried out. Such annealing is carried out at about 650° C. Since this temperature is well above the recrystallisation temperature of 500° C, recrystallisation will be accelerated so that it will be complete in a matter of minutes on attaining the maximum temperature.

It should be noted that process annealing is a *sub-critical* operation, that is, it takes place below the lower critical temperature (A_1). For this reason, although recrystallisation is promoted, there is no phase change and the constituents ferrite and cementite remain present in the structure throughout the process.

Process annealing is generally carried out in either batch-type or continuous furnaces, usually with an inert atmosphere of burnt coal gas, though cast-iron annealing "pots" are still used, their lids being luted on with clay.

b) Spheroidised annealing

The Spheroidised condition is produced by annealing the steel at a temperature between 650 and 700 ° C, just below the lower critical temperature. During this treatment cementite forms as spheroidal particles in a ferrite matrix, putting the steel into a soft, but very tough, condition.

Since the temperature involved are sub critical no phase changes take place and spheroidisation of the cementite is purely a surface tension effects. This is referred to as the a spheroidisation of pearlitic cementite and the process is shown diagrammatically in figure 3.



Figure 3. The Spheroidisation of Pearlitic Cementite.

c) Full annealing

It is the treatment given to produce the softest possible condition in a hypoeutectoid steel. It involves heating the steel to a temperature within the range $30 - 50$ °C above the upper critical temperatures and then allowing the steel to cool slowly within the furnace. This produces a structure containing coarse pearlite.

This results in the formation of fine grains of austenite that transform into relatively fine grains of ferrite and pearlite or pearlite and cementite (depending upon the carbon content) as the steel is slowly cooled to room temperature, usually in the furnace.

Full annealing is an expensive treatment and when it is not absolutely essential for the steel to be in a very soft condition, but a reasonably soft and ductile material is required, the process known as normalizing is used instead.

Ferrite, which then begins to precipitate in accordance with the equilibrium diagram, deposits first at the grain boundaries of the austenite, thus revealing, in the final structure, the size of the original austenite grains. The remainder of the ferrite is then precipitated along certain crystallographic planes within the lattice of the austenite. This gives rise to a directional precipitation of the ferrite, as shown in figure 4. and Plate , representing typically what is known as a Widmanstatten structure. This type of structure was first encountered by Widmanstatten in meteorites, which may be expected to exhibit a coarse structure in view of the extent to which they are overheated during their passage through the upper atmosphere. The mesh-like arrangement of ferrite in the Widmanstatten structure tends to isolate the stronger pearlite into separate patches, so that strength, and more particularly toughness, are impaired. The main characteristics of such a structure are, therefore, weakness and brittle-ness, and steps must be taken to remove it either by heat-treatment or by mechanical working. Hot-working will effectively break up this coarse as-cast structure and replace it by a fine-grained material, but in this instance we are concerned with retaining the actual shape of the casting. Heat-treatment must therefore be used to effect the necessary refinement of grain.

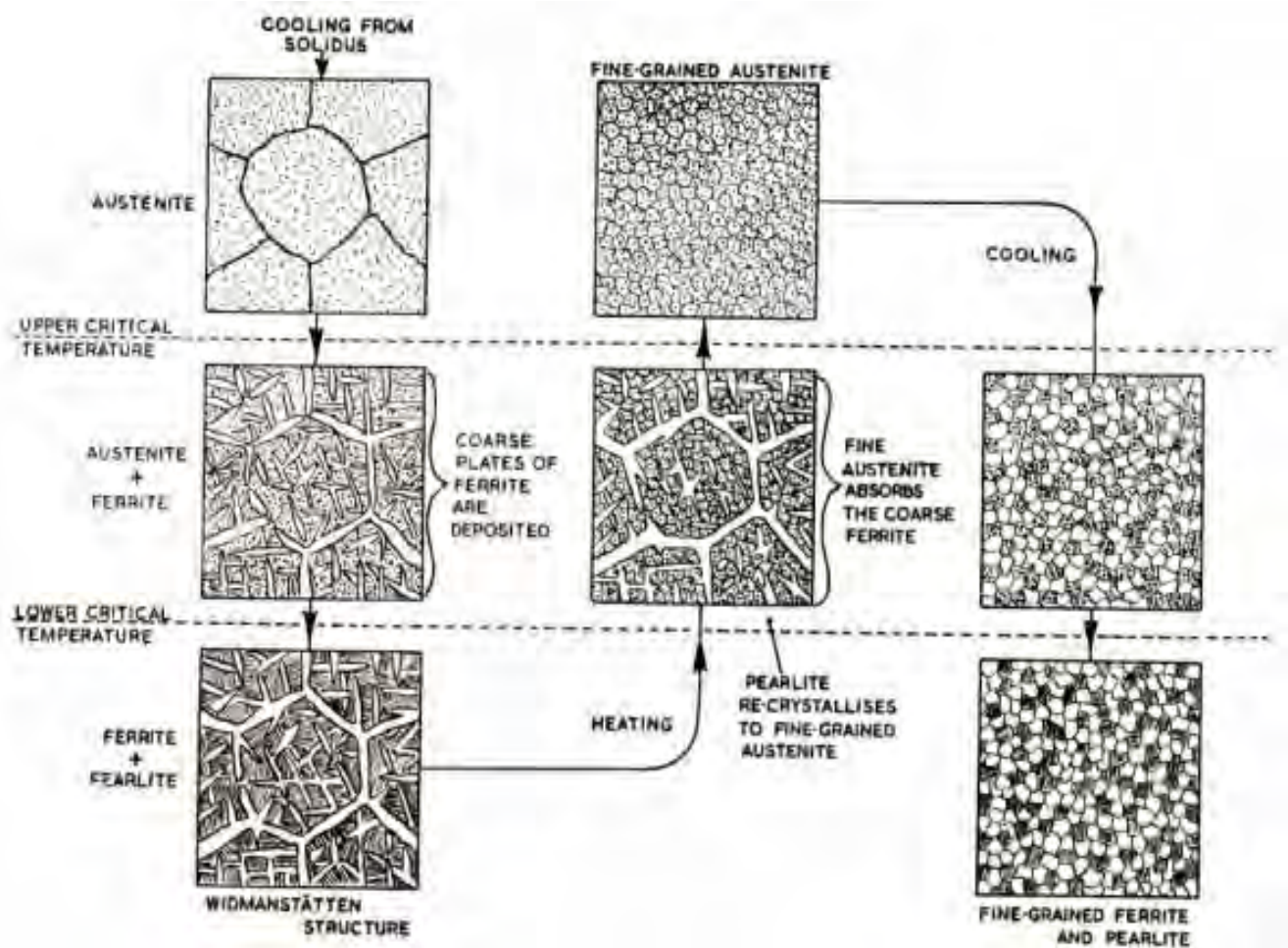


Figure 4. The structural effects of heating a steel casting to a temperature just above its upper critical , followed by cooling to room temperature.

This operation need a very specific controlling on the heat temperature of annealing because if any fault is occrou, it will make some un desired phases in the steel such as :-

1) Over heating

Overheating during annealing, or heating for too long a period in the austenitic range, will obviously cause grain growth of the newly formed austenite crystals, leading to a structure almost as bad as the original Widmanstatten structure. For this reason the requisite annealing temperature should not be exceeded, and the

casting should remain in the austenitic range only for as long as is necessary to make it completely austenitic. In fact, castings are sometimes air-cooled to about 650° C and then cooled more slowly to room temperature, by returning to a furnace to prevent stresses due to rapid cooling from being set up.

2) Burning (Excessive over heating)

Excessive overheating will probably cause oxidation, or "burning", of the surface, and the penetration by oxide films of the crystal boundaries following \square ecarburization of the surface.

Such damage cannot be repaired by heat-treatment, and the castings can only be scrapped. To prevent "burning", castings are often annealed in cast-iron boxes into which they are packed with lime, sand, cast-iron turnings or carbonaceous material, according to the carbon content of the castings.

3) Under-quenealing

As the lower critical temperature (723 °C) is reached on heating, the patches of pearlite change to austenite, but these crystals of austenite are very small, since each grain of pearlite gives rise to a number of new austenite crystals. As the temperature rises, the Widmanstatten-type plates of ferrite are dissolved by the austenite until, when the upper critical temperature is reached, the structure consists entirely of fine-grained austenite. Cooling causes re-precipitation of the ferrite, but, since the new austenite crystals are small, the precipitated ferrite will also be distributed as small particles. Finally, as the lower critical temperature is reached, the remaining small patches of austenite will transform to pearlite.

2. Normalising

The process resembles full annealing except that, whilst in annealing the cooling rate is deliberately retarded, in normalising the cooling rate is accelerated by taking the work from the furnace and allowing it to cool in free air. Provision must be made for the free circulation of cool air, but draughts must be avoided.

In the normalising process, as applied to hyper-eutectoid steels, it can be seen that the steel is heated to approximately 50° C above the upper critical temperature line. This ensures that the transformation to fine grain austenite corrects any grain growth or grain distortion that may have occurred previously. Again, the steel is cooled in free air and the austenite transforms into fine grain pearlite and cementite. The fine grain structure resulting from the more rapid cooling associated with normalising gives improved strength and toughness to the steel but reduces its ductility and malleability. The increased hardness and reduced ductility allows a better surface finish to be achieved when machining. (The excessive softness and ductility of full annealing leads to local tearing of the machined surface.)

The type of structure obtained by normalising will depend largely upon the thickness of cross-section, as this will affect the rate of cooling. Thin sections will give a much finer grain than thick sections, the latter often differing little in structure from an annealed section.

Although highly successful, this procedure tied up an excessive amount of working capital and space and nowadays heat treatment is preferred as the work in progress is turned round more quickly.

3. Hardening

When a piece of steel, containing sufficient carbon, is cooled rapidly from above its upper critical temperature it becomes considerably harder than it would be if allowed to cool slowly.

This involves rapidly quenching the steel, from a high temperature into oil or water. Hypereutectoid steels are heated to (30- 50 °C) above the upper critical temperature prior to quenching. It is possible that some cementite grain boundaries.

Consequently, hypereutectoid steels are hardened by quenching from (30- 50 °C) above the lower critical temperature. At this temperature the structure because one of spheroidal cementite particles in an austenite matrix.

The degree of hardness produced can vary, and is dependent upon such factors as the initial quenching temperature; the size of the work; the constitution, properties and temperature of the quenching medium; and the degree of agitation and final temperature of the quenching medium.

To harden a piece of steel, it must be heated then quenched in some media which will produce in it the desired rate of cooling . the medium used will depend upon the composition of the steel and the ultimate properties required.

The quenching medium is chosen according to the rate at which it is desired to cool the steel. The following list of media is arranged in order of quenching speeds:

5 % Caustic soda

5 – 20 % Brine

Cold water

Warm water

Mineral oil.

4. Tempering

A quench-hardened plain carbon steel is hard, brittle and hardening stresses are present. In such a condition it is of little practical use and it has to be reheated, or *tempered*, to relieve the stresses and reduce the brittleness.

This temperature will remove internal stress setup during quenching, remove some, or all, of the hardness, and increase the toughness of the material.

Tempering causes the transformation of martensite into less brittle structures. Unfortunately, any increase in toughness is accompanied by some decrease in hardness. Tempering always tends to transform the unstable martensite back into the stable pearlite of the equilibrium transformations.

Tempering temperatures below 200 °C only relieve the hardening stresses, but above 220 °C the hard, brittle martensite starts to transform into a fine pearlitic structure called *secondary troostite* (or just '**troostite**'). Troostite is much tougher although somewhat less hard than martensite and is the structure to be found in most carbon-steel cutting tools.

Tempering above 400 °C causes any cementite particles present to "ball-up" giving a structure called *sorbite*. This is tougher and more ductile than troostite and is the structure used in components subjected to shock loads and where a lower order of hardness can be tolerated, for example springs. It is normal to quench the steel once the tempering

For most steels, cooling from the tempering temperature may be either cooling in air, or quenching in oil or water. Some alloy steels, however, may become embrittled if slowly cooled temperature has been reached. From the tempering temperature, and these steels have to be quenched.

Engineering Materials

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Cast Iron

Introduction :

Cast iron is the name given to those ferrous metals containing more than 1.7 % carbon. It is similar in composition to crude pig iron as produced by the blast furnace. Unlike steel, it is not subjected to an extensive refinement process. After the pig iron has been remelted in a cupola furnace ready for casting, selected scrap iron and scrap steel added to the melt to give the required composition.

Although normal grades of cast iron are not particularly strong, and are quite brittle, they are widely used as engineering materials, because of their cheapness, ease of melting and casting, very good machineable and a high damping capacity, resistance to wear and compressive strength are required, it has a high fluidity which makes it easy to cast into intricate shapes and it has a melting point between 1147 and 1250° C, which is substantially lower than the melting point for mild steel.

The complete iron carbon diagram as in figure 1, it will be noticed that a eutectic of austenite and cementite which contains 4.3% carbon is formed at 1131° C. (This eutectic point, like the eutectoid composition in the case of steel at 0.83% carbon, may be moved farther to the left of the diagram by the elements present, so that a cast iron containing less than 4-3% carbon may be of eutectic composition.) In accordance with the equilibrium diagram, a cast iron containing more than the eutectic amount of carbon may be expected to begin solidification by depositing some cementite. Unless cooling is very rapid, however, graphite may precipitate instead, due to instability of the cementite caused by other elements (notably silicon) present. This primary graphite, which separates out from the melt during cooling, forms as large flakes, usually called "kish". The finer flakes of graphite occurring in grey cast iron are those which are formed by decomposition of the cementite after solidification Graphite flakes of this

latter type exist in cast irons of compositions either above or below the eutectic, and produce rather better mechanical properties.

The presence of graphite gives a softer iron which machines well because of the effect of the graphite flakes in forming chip cracks in advance of the edge of the cutting tool.

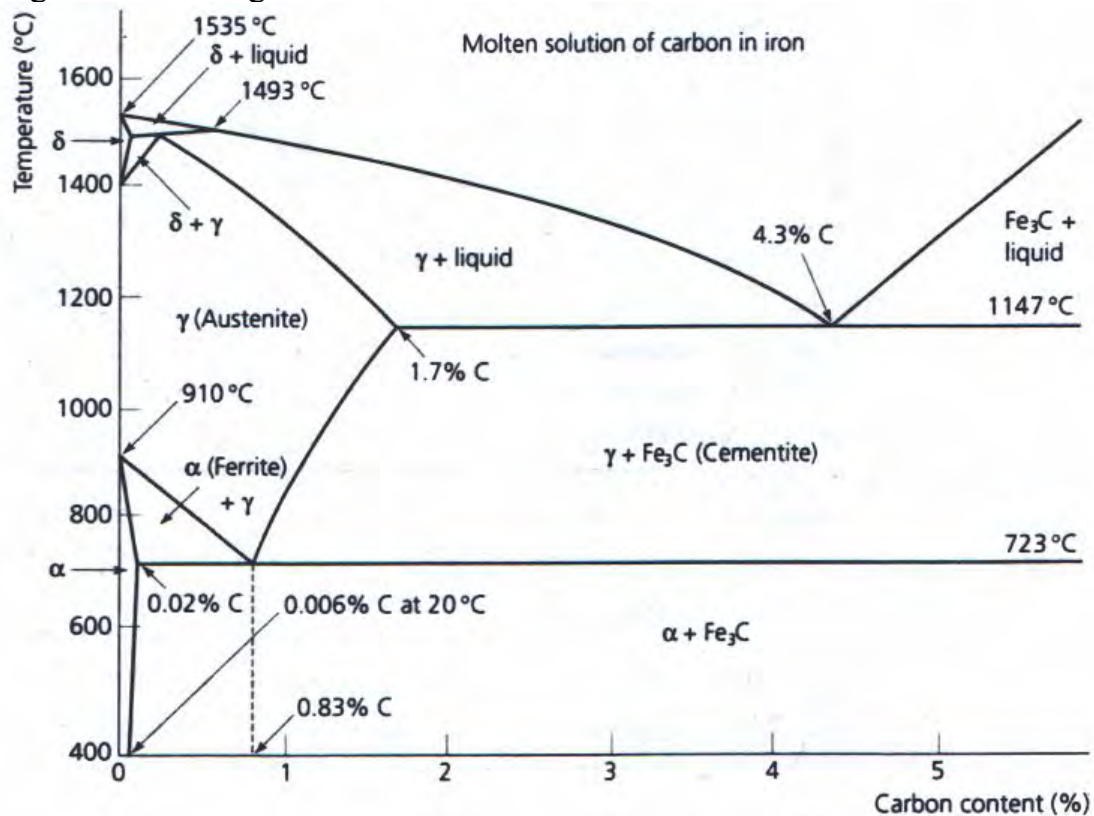


Figure 1. The phase equilibrium diagram of the iron.

As for figure 2. shows that there is a eutectic when there is 4.3% carbon present. At this composition the molten metal solidifies at 1147° C into austenite (γ phase) and cementite (Fe₃C). Unless cooling is very rapid, graphite will be precipitated out due to the instability of the cementite as a result of some of the impurities present (particularly silicon). As cooling proceeds, further graphite is precipitated out from the austenite. At 723° C providing cooling is slow enough, the remaining austenite (γ phase) changes into ferrite (α phase). Thus at room temperature the composition consists of ferrite plus large flakes of graphite together with fine flakes of graphite formed by the decomposition of the cementite after solidification.

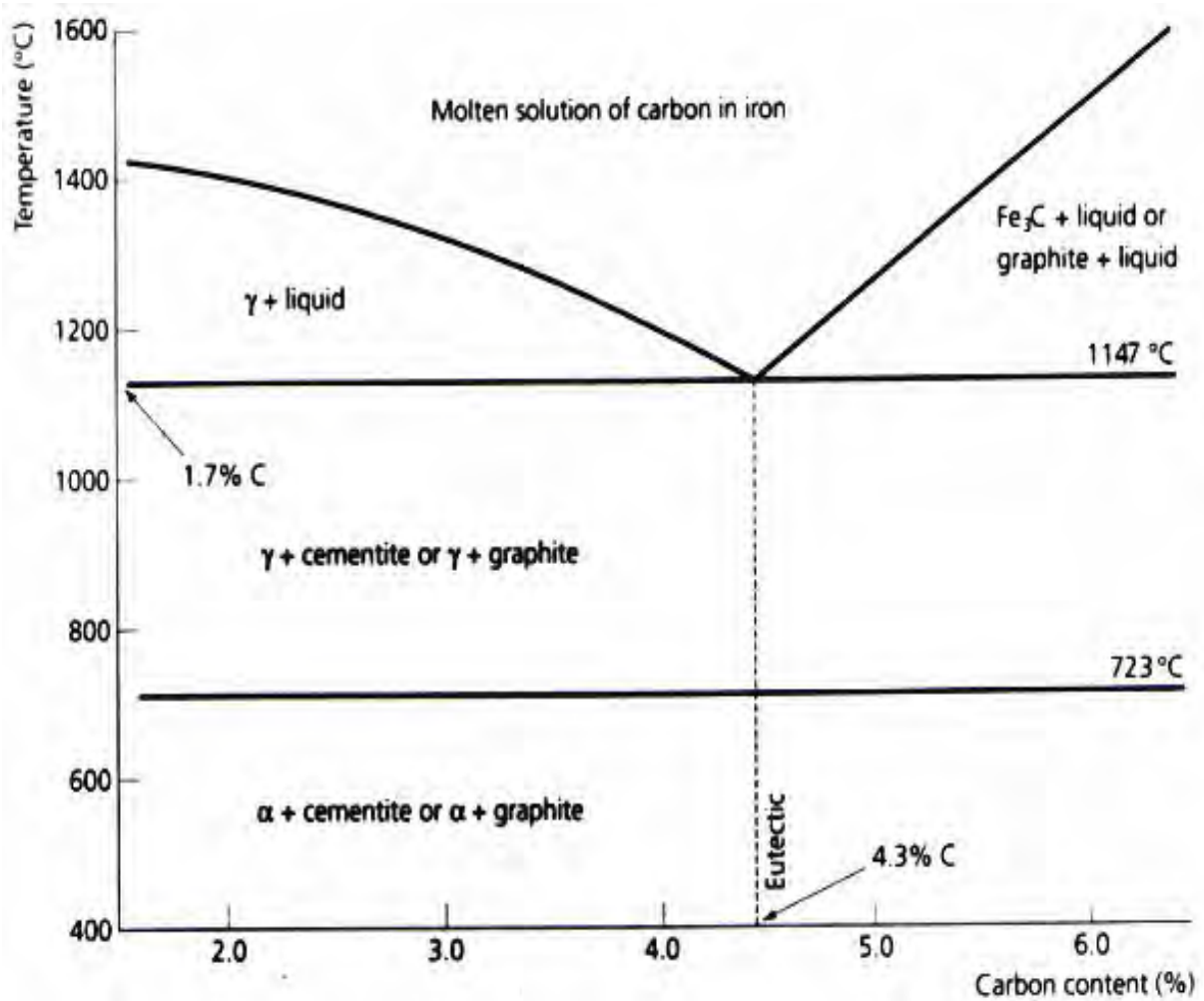


Figure 2. Section of the iron-carbon phase equilibrium diagram.

For the relationship between carbon content, microstructure and mechanical properties figure 3 is shown below.

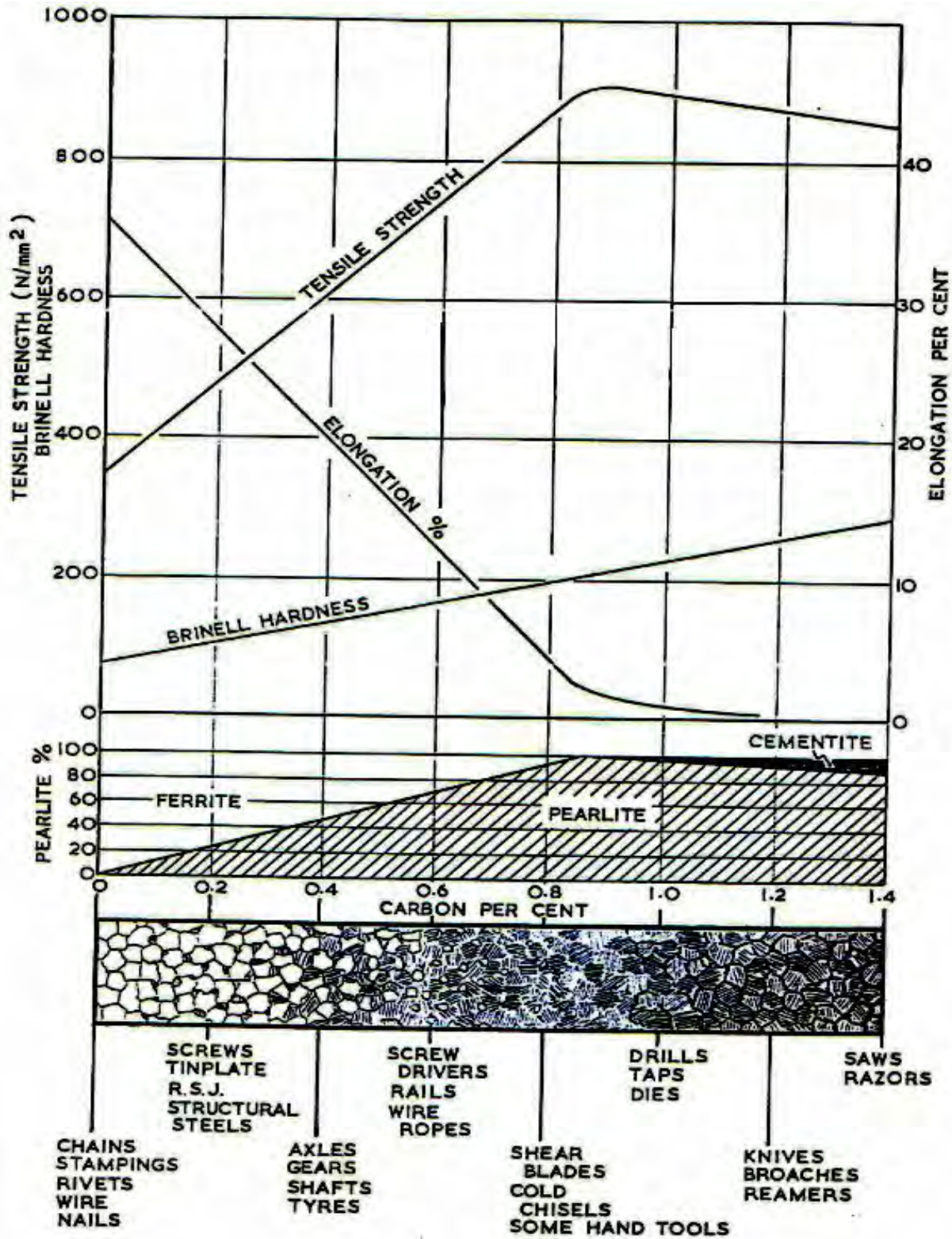


Figure 3. Diagram showing the relationship between carbon content, microstructure and mechanical properties of plain carbon steels in the normalized condition.

The structure of cast iron is affected by the following factors:-

- a) **The rate of solidification.** Slow rates of solidification allow for graphite formation and castings made in sand moulds tend to solidify gray. More rapid solidification will tend to give white irons structures. Metal chills are sometimes inserted into parts of sand moulds in those areas where a high surface hardness is required.
- b) **Carbon content.** The higher the carbon content of the iron, the greater will be the tendency for it to solidify grey.
- c) **The presence of other elements.** Some elements promote the formation of graphite in an iron structure. Silicon and nickel have strong graphitising tendencies, as shown in figure 4.

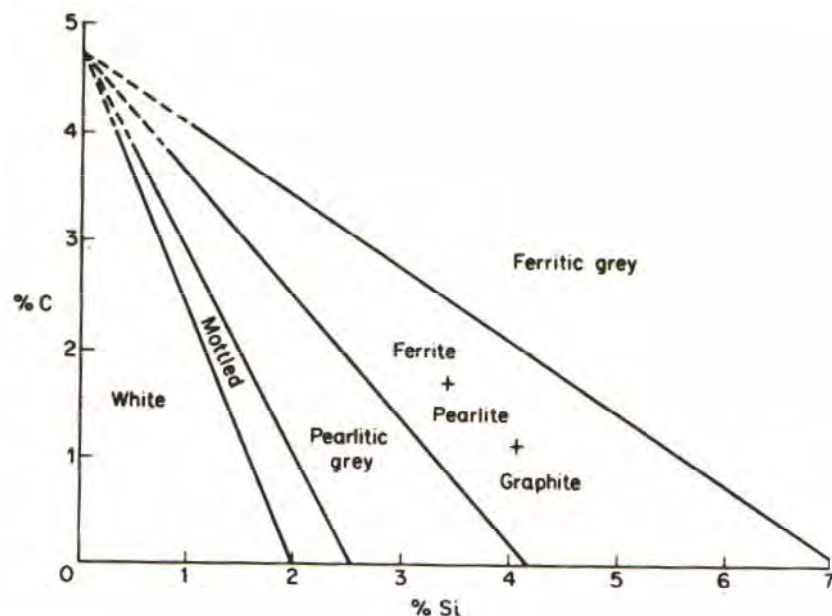


Figure 4. Effect of silicon and carbon content on the structure of cast irons.

- d) **The effect of heat treatment.** The prolonged heating of a white iron will cause graphitization to occur. This phenomenon is used as the basis for the production of malleable irons. Graphite is less dense than cementite and, if cementite decomposes into ferrite and graphite during service, this change will be accompanied by a reduction in the density of the iron, and a corresponding increase in dimensions. This phenomenon

is termed the growth of cast irons, and irons for high-temperature service must be in a fully graphitised state before being put into use.

- e) **The rate of cooling on the structure of cast iron.** A high rate of cooling during solidification tends to prevent the decomposition of cementite in an iron which, on slow cooling, would become graphitic. This effect is important in connection with the choice of a suitable iron for the production of castings of thin section. Supposing an iron which, when cooled slowly, had a fine grey structure containing small flakes of graphite were chosen for such a purpose. In thin sections it would cool so rapidly that decomposition of the cementite could not take place, and a thin section of completely white iron would result. Such a section would be brittle and useless.] This effect is illustrated by casting a "stepped bar" of iron of a suitable composition. Here, the thin "steps" have cooled so quickly that no decomposition of the cementite has occurred, as indicated by the white fracture and the high Brinell figures. The thicker steps, having cooled more slowly, are graphitic and consequently softer. Due to the chilling effect exerted by the mould, most castings have a hard white skin on the surface. This is often noticeable when taking the first "cut" in a machining operation.

In casting thin sections, then, it is necessary to choose an iron of rather coarser grey fracture than is required in the finished casting. That is, the iron must have a higher silicon content than that used for the production of castings of heavy section.

Carbon can exist in two forms in cast iron, namely as free graphite or combined with some of the iron to form iron-carbide (cementite). These two varieties are usually referred to as "**graphitic carbon**" and "**combined carbon**" respectively, and the total amount of both types in the specimen of iron as "**total carbon**".

This makes the casting to be classified as either white or grey.

These terms arise from the appearance of a freshly fractured surface.

Gray iron structure :-

An iron that contains graphite in its structure shows a fracture surface that is grey and dull in color, as shown in figure 5.

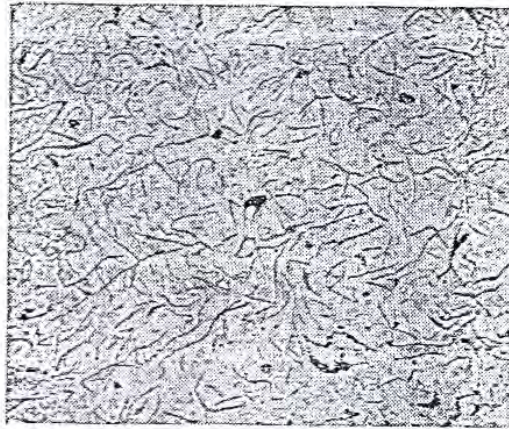


Figure 5. Grey cast iron.

Properties and uses of grey cast irons:

These are the most widely used cast irons and they vary in composition according to specific applications.

Cast irons Cast irons requiring high fluidity are used for very intricate mouldings for decorative iron work and architectural tracery. They lack mechanical strength since the high fluidity is obtained by ensuring that the melt has a high silicon content (2.5-3.5%) and a high phosphorus content (approximately 1.5%). It is the high phosphorus content which reduces the strength of the metal.

General-purpose engineering irons have to have reasonable mechanical strength. Ideally they should have fine graphite flakes in a matrix of pearlite. Such a cast iron would combine good mechanical properties with good machinability. The silicon content would be dependent upon the thickness and mass of the casting, varying between 2.5 % for thin sections and about 1.5% for castings with thick sections. The phosphorus content would be kept low to improve toughness and shock resistance, although up to 0.8% may be present to improve fluidity. Sulphur must be kept below 0.1 % to avoid segregation, hard spots and embrittlement.

Local hardening of grey iron castings (e.g. slideways) can be achieved by chilling. This is done by introducing 'chills' or metal plates into the mould just behind the surface layer of sand to promote rapid cooling and the formation of cementite. The hardness occurs only at the surface of the casting and the core

remains grey and tough.

Large heavy castings do not require a high silicon content as they naturally cool slowly and there is adequate time for any cementite to break down into ferrite and flake graphite. A typical composition would be (1.2-1.5)% silicon, 0.5% phosphorus and 0.1% sulphur.

White iron structure:-

If, however, the whole of the carbon content of an iron is in the combined form, as cementite, a fresh fracture surface appears bright and silvery, and this is termed a white iron structure, as shown in figure 6.

White irons are exception alloy hard, but brittle, it is not often used, except as the basis for the production of malleable irons, although portions of many sand casting are made to solidify while, by the insertion of chills in the sand mould, in order to produce hard and wear resistance surfaces in parts of the casting.

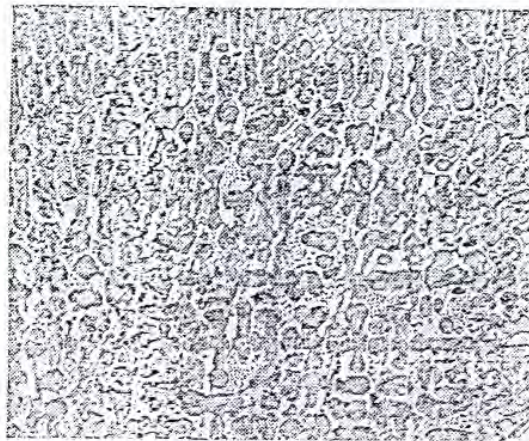


Figure 6. White cast iron.

Properties and uses of white cast iron :-

White cast irons are little used except as a basis for malleable cast irons are wear resistant but lack ductility and they break easily since they are very brittle are virtually un machinable except by grinding.

Alloying elements and impurities:

Cast irons are not solely alloys of iron and carbon as the phase equilibrium diagram would suggest, but complex alloys in which impurities such as sulphur, phosphorus and alloy elements such as silicon and manganese have a significant influence on the properties of the casting

1. Silicon

This element is used to soften cast irons by promoting the formation of flake graphite at the expense of cementite. The silicon content is increased in irons used for light or thin components which might chill harden by cooling too quickly in the mould and becoming hard and brittle. The addition of significant amounts of silicon can reduce the eutectic composition down to 3.5 % carbon. Thus, at a constant rate of cooling, the addition of silicon to a cast iron having 3 % carbon will have the following effects.

- Ferritic grey cast iron is produced with 3 per cent silicon.
- Ferritic /pearlitic cast iron is produced with 2 per cent silicon.
- pearlitic cast iron is produced with 1.5 percent silicon.
- White cast iron is produced with no silicon.

Providing sufficient silicon has been added to break down the cementite into flake graphite (3% silicon in this example) there is no benefit in adding extra silicon. In fact, the presence of excess silicon will lead to increased hardness and brittleness.

2. Sulphur

Sulphur is an impurity carried over from the fuel used in the blast furnace during the extraction of the iron from its ore. The presence of sulphur in cast irons, even in small quantities, has the effect of stabilising the cementite and preventing the formation of flake graphite. Thus, sulphur hardens the cast iron. It also causes embrittlement due to the formation of iron sulphide (FeS) at the grain boundaries.

3. Manganese

The addition of this element in small quantities is essential in all ferrous metals as it combines with any residual sulphur present to form manganese sulphide (MnS). Unlike ferrous sulphide, manganese sulphide is insoluble in the molten iron and floats to the top of the melt to join the

slag. Thus by removing the sulphur, the manganese indirectly softens the cast iron and also removes a source of embrittlement. Increasing the manganese content beyond that required to neutralise the sulphur has the effect of stabilising the cementite and causing hardness in the iron, just as the sulphur did, but without any embrittlement. Thus it is important to balance the amount of manganese, sulphur and silicon present with great care. Manganese also promotes grain refinement and increases the strength of the cast iron.

4. Phosphorus

Like sulphur, this is a residual impurity from the extraction process. It is present in cast iron as iron phosphide (Fe_3P). This phosphide forms a eutectic with ferrite in grey cast irons, and with ferrite and cementite in white cast irons. Since these eutectics melt at only 950°C , high phosphorus content cast irons have great fluidity. Cast irons containing 1 per cent phosphorus are thus very suitable for the production of thin section castings and highly intricate ornamental castings. Unfortunately phosphorus, like sulphur, causes hardness and embrittlement in the cast iron and the amount present must be kept to a minimum in castings where shock resistance and strength are important.

Types of cast iron

There are several types of cast iron such as :

1) Alloy cast iron

Although complex alloys, such cast irons are still referred to as common cast iron: the term alloy cast irons being reserved for those cast irons containing substantial amounts of such metallic elements as chromium, nickel, etc. Alloying elements may be added to cast irons in order to improve their properties, and alloy cast irons have been developed to give high-strength materials, hard and abrasion-resistance materials, corrosion resistance irons and irons for high-temperature service.

The alloying elements in cast irons are similar to those in alloy steels, which are as follows:

- **Nickel** This is used for grain refinement, to add strength, and to promote the formation of free graphite. Thus it toughens the casting.

- ***Chromium*** This stabilises the combined carbon (cementite) present and thus increases the hardness and wear resistance of the casting. It also improves the corrosion resistance of the casting, particularly at elevated temperatures. As in alloy steels, nickel and chromium tend to be used together because they have certain disadvantages when used separately which tend to offset their advantages. However, when used together the disadvantages are overcome, whilst the advantages are retained.
- ***Copper*** This is used very sparingly as it is only slightly soluble in iron; however, it is useful in reducing the effects of atmospheric corrosion.
- ***Vanadium*** This is used in heat-resisting castings as it stabilises the carbides and reduces their tendency to decompose at high temperatures.
- ***Molybdenum*** This dissolves in the ferrite and, when used in small amounts (0.5 %), it improves the impact strength of the casting. It also prevents 'decay' at high temperatures in castings containing nickel and chromium. When molybdenum is added in larger amounts it forms double carbides, increases the hardness of castings with thick sections, and also promotes uniformity of the microstructure.

Martensite Martensitic cast irons contain between 4 and 6 % nickel and approximately 1 per cent chromium, for example, 'Ni-hard' cast iron. It is naturally martensitic in the cast state but, unlike alloys with rather less nickel and chromium, it does not need to be quenched thus reducing the possibility of cracking and distortion. It is used for components which need to resist abrasion. It can only be machined by grinding.

Austenite Austenitic cast irons contain between 11 and 20 per cent nickel and up to 5% chromium. These alloys are corrosion resistant, heat resistant, tough and non magnetic. Since the melting temperatures of alloy cast irons can be substantially higher than those for common grey cast irons, care must be taken in the selection of moulding sands and the preparation of the surfaces of the moulds. Increased venting of the moulds is also required as the higher temperatures cause more rapid generation of steam and gases. The furnace and crucible linings must also be suitable for the higher temperatures and the inevitable increase in maintenance costs is also a significant factor when working with high-alloy cast irons.

2) Malleable cast iron

Malleable cast irons are produced from white cast irons by a variety of heat-treatment processes, depending upon the final composition and structure required. As their name implies, malleable cast irons have increased malleability and ductility, increased tensile strength, and increased toughness.

1. *Black-heart process*

In this process the white iron castings are heated in airtight boxes out of contact with air at 850-950 °C for 50-170 hours, depending upon the mass and thickness of the castings. The effect of this prolonged heating is to break down the iron carbide (cementite) of the white cast iron into small rosettes of graphite.

The name 'black-heart' comes from the darkened appearance of the iron, when fractured, resulting from the formation of free graphite.

It is used in the wheel hubs, break drums, conduit fitting control levers and pedals.

2. *White-heart process*

In this process the castings are packed into airtight boxes with iron oxide in the form of high-grade ore. They are then heated to about 1000 °C for between 70 and 100 hours, depending upon the mass and thickness of the castings. The ore oxidises the carbon in the castings and draws it out, leaving a ferritic structure near the surface and a pearlitic structure near the centre of the casting. There will also be some fine rosettes of graphite. White-heart castings behave much as expected of a mild steel casting, but with the advantage of a very much lower melting point and higher fluidity at the time of casting.

It is used in the wheel hubs, bicycle and motor cycle frame fittings, gas, water and steam pipe fittings.

3. *Pearlitic process*

This process is similar to the black-heart process inasmuch as the castings are heated to 850-950 ° C for 50-170 hours in a non-oxidising environment. As in the black-heart process the iron carbide (cementite) breaks down into austenite and free graphite. However, in the pearlitic cast iron process, rapid cooling prevents the austenite changing into ferrite and graphite, and a pearlitic structure is produced instead. Since this 'pearlitic cast iron' also has a fine grain resulting from the rapid cooling, it is harder, tougher and has a higher tensile strength than black-heart cast iron. However, there is a marked reduction in malleability and ductility. Pearlitic malleable irons can be produced by increasing the manganese content of the melt from 1.0-1.5 per cent. This inhibits the production of free graphite and encourages the formation of cementite and pearlite.

It is used in the gears, couplings, axle housing, differential housing and components.

Properties and uses of malleable cast irons:

Malleable irons exploit the excellent casting properties of cast iron during the casting process, after which they are converted by heat-treatment processes into a composition and structure whose properties resemble that of a low-carbon steel. This results in castings which are stronger and much less brittle than ordinary cast irons and are widely used in the automobile, agricultural machinery and machine tool industries for the manufacture of small and medium sized stressed components.

Malleable iron castings are also used in the electrical industry for conduit fittings, switch gear cases and components.

3) Spheroidal graphite cast iron

(Also known as " S.G. cast iron" "nodular iron" or "ductile iron".)

In a normal grey cast iron the graphite flakes are long and thin, and tend to be pointed at their ends, as shown in figure 7. These long, thin flakes, having negligible tensile strength, act as discontinuities in the structure; whilst the sharp-pointed ends of the flakes introduce points of stress concentration. In S.G. cast iron the graphite flakes are replaced by spherical particles of graphite (Plate I54A), so that the metallic matrix is much less broken up, and the sharp "stress raisers" are eliminated.

The formation of this spheroidal graphite is effected by adding small amounts of cerium or magnesium to the molten iron just before casting. Since both of these elements have strong carbide-forming tendencies, the silicon content of the iron must be high enough (at least 2.5%) in order to prevent the formation, by chilling, of white iron in thin sections. Magnesium is the more widely used, and is usually added (as a nickel-magnesium alloy) in amounts sufficient to give a residual magnesium content of 0.1% in the iron. S.G. cast irons produced by the magnesium process have tensile strengths of up to 775 N/mm^2 .

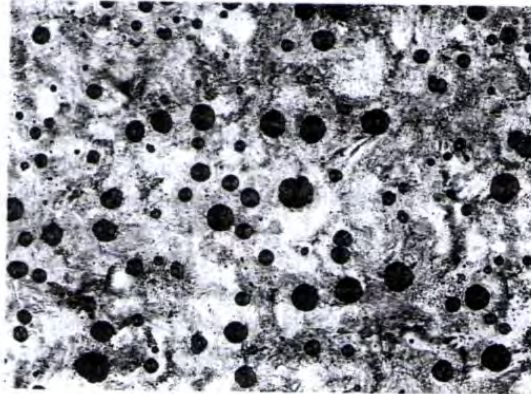


Figure 7. Spheroidal graphite cast iron.

Properties and uses of spheroidal graphite cast irons:

Spheroidal graphite cast irons are now used for quite highly stressed components in the automobile industry. By designing components with this material in mind, spheroidal graphite castings can, in some instances, replace steel forgings at much lower cost; for example: camshafts, crankshafts and differential gear carriers for motor vehicles.

4) Inoculated cast iron (حديد الزهر المطعم العالي)

If an ordinary cast iron is super heated to, say, 1500° C before casting, the formation of graphite is delayed and does not begin until well below the solidification range. This leads to the production of very small graphite flakes, which is a desirable feature. Unfortunately, much brittle cementite is also retained since graphitisation is incomplete under these conditions of cooling. Hence the super-heated iron is "inoculated" with some refractory material which will produce many small particles or nuclei, which, in turn, will promote the formation of fine graphite flakes. "Meehanite" (a registered proprietary name) is an iron which would normally solidify "white" but which has been inoculated with calcium silicide just before casting. Ferrosilicon, graphite and various commercial inoculants are used in other "trademarked" cast irons. In all of these products improved mechanical properties are obtained as a result of the small-flaked graphite induced by inoculation.

Engineering Materials

9

Alloy Steels

Introduction :

Steels are, essentially, alloys of iron and carbon, containing up to 1.5 % of carbon. Steel is made by oxidizing away the impurities that are present in the iron produced in the blast furnace.

The earliest attempt to produce an alloy steel was in 1822 and it has progressed in producing the alloy steel because of using alloy steel in those industries upon modern civilization largely depends.

Pure metal objects are used where good electrical conductivity, good thermal conductivity, good corrosion resistance or a combination of these properties are required. Therefore alloys are mainly used for structural materials since they can be formulated to give superior mechanical properties.

It is called as alloy steel because there are other elements added to the iron beside the carbon with specific amount for each element. These elements improve the properties of the alloying steel and make it used with applications more than the carbon steel. So the most used elements with the alloy steel and with their amount as a percentage of :

- 2 % Manganese (Mn)
- 0.5 % Chrome (Cr) or Nickel (Ni)
- 0.3 % Tungsten (W) or Cobalt
- 0.1 % Molybdenum (Mo) or Vanadium
- different amount of Aluminum (Al), Copper (Cu) and Silicon (Si).

Alloys steels are generally classified into **two major types** depending on the structural classification :

- Low alloy steels :

It is one that possesses similar microstructure to, and requires similar heat treatment to, plain carbon steels. These generally contain up to 3 – 4 % of one or more alloying elements for purpose of increasing strength, toughness and hardenability. The applications of low alloy steels are similar to those of plain carbon steels of similar carbon contents. Low alloy steels containing nickel are particularly suitable for applications requiring resistance to fatigue.

- High alloy steels :

Those steels that possess structures, and require heat treatments, that differ considerably from those of plain carbon steels. A few examples of high alloy steels are given below:

1. High-speed tool steels

Tungsten and chromium form very hard and stable carbides. Both elements also raise the critical temperatures and, also, cause an increase in softening temperatures. High carbon steels rich in these elements provide hard wearing metal-cutting tools, which retain their high hardness at temperature up to 600°C. a widely used high-speed tool steel composition is containing 18% of tungsten, 4% of chromium, 1% of vanadium and 0.8% of carbon .

This high-alloy content martensite does not soften appreciably until it is heated at temperatures in excess of 600°C making them usable as cutting tools at high cutting speeds.

2. Stainless steels

When chromium is present in amounts in excess of 12% , the steel becomes highly resistance to corrosion, owing to protective film of chromium oxide that forms on the metal surface. Chromium also raises the α to γ transformation temperature of iron, and tends to stabilize ferrite in the structure.

There are several types of stainless steels, and these are summarized below:

- a) **Ferritic stainless steels** contain between 12- 25% of chromium and less than 0.1% of carbon.
- b) **Martensitic stainless steels** contain between 12-18 % of chromium, together with carbon contents ranging from 0.1 to 1.5 %
- c) **Austenitic steels** contain both chromium and nickel. When nickel is present, the tendency of nickel to lower the critical temperatures overrides the opposite effect of chromium, and the structure may become wholly austenitic.

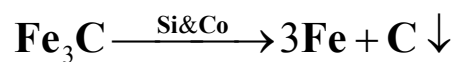
3. *Maraging steels*

These are very high-strength materials that can be hardened to give tensile strengths up to 1900 MN/m². They contain 18% of nickel, 7% of cobalt and small amounts of other elements such as titanium, and the carbon content is low, generally less than 0.05% .

A major advantage of maraging steels is that after the solution treatment they are soft enough to be worked and machined with comparative ease.

Alloy elements can be classified depending on the using of the alloy (its application) or according to the basic influence of the element on the alloy steel properties as follow:

1. **alloying elements tend to make carbides** such as Cr, W, Ti, V and Mo it is used in the applications that needs to higher hardness.
2. **alloying elements due to analyzing carbides** such as Ni, Al, Co and Si.



3. **alloying elements stabilizing austenite γ** such as Ni, Co, Cu and Mn.
4. **alloy elements stabilizing ferrite α** such as Cr, W, V, AL and Si.

The *principal effects* which these alloying elements have on the microstructure and properties of a steel can be classified as follows:

1. The Effect on the Allotropic Transformation Temperatures.

Some elements, notably nickel, manganese, cobalt and copper, raise the A_4 temperature and lower the A_3 temperature, as shown in figure 1. In this way these elements, when added to a carbon steel, tend to stabilise austenite (γ) and increase the range of temperature over which austenite can exist as a stable phase.

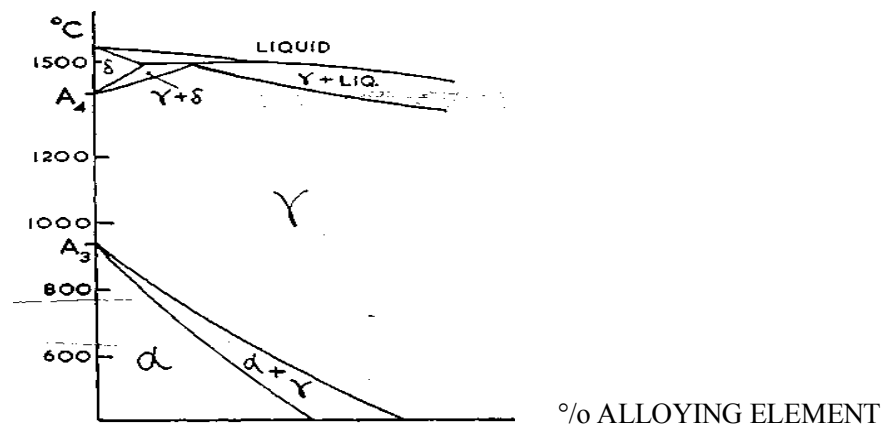


Figure 1.—Relative Effects of the Addition of an Alloying Element on the Allotropic Transformation Temperatures at A_3 and A_4 which tending to stabilise γ .

Other elements, the most important of which include chromium, tungsten, vanadium, molybdenum, aluminum and silicon, have the reverse effect, in that they tend to stabilize ferrite (α) by raising the A_3 temperature and lowering the A_4 , as indicated in figure 2.

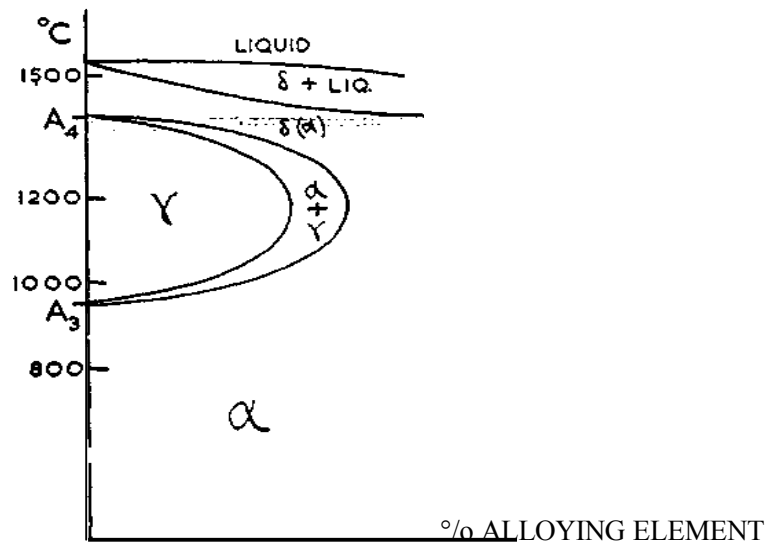


Figure 2. Relative Effects of the Addition of an Alloying Element on the Allotropic Transformation Temperatures at A_3 and A_4 tending to stabilize α .

2. The Effect on the Stability of the Carbides.

Some of the alloying elements form very stable carbides when added to a plain carbon steel. This generally has a hardening effect on the steel, particularly when the carbides formed are harder than iron carbide itself. Such elements include chromium, tungsten, vanadium, molybdenum, titanium and manganese [these elements are called the carbide stabilizer]. When more than one of these elements are present, a structure containing complex carbides is often formed.

3. The effect on grain growth.

The rate of crystal growth is accelerated, particularly at high temperatures, by the presence of some elements, notably **chromium**.

Fortunately, grain growth is retarded by other elements, notably nickel and vanadium, whose presence-thus produce a steel which is less sensitive to the temperature conditions of heat-treatment.

4. The Displacement of the Eutectoid Point.

The addition of an alloying element to carbon steel displaces the eutectoid point towards the left of the equilibrium diagram. That is, a steel can be completely pearlitic even though it contains less than 0.83% carbon. For example, the addition of 2.5% manganese to a steel containing 0.65% carbon produces a completely pearlitic structure in the normalized condition as shown in figure 3.

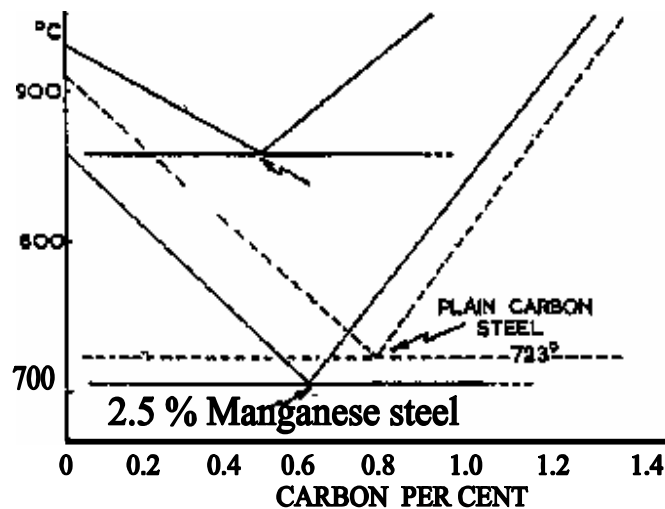


Figure 3. The Effects of Manganese and Titanium on the Displacement of the Eutectoid Point in Steel.

Similarly, although a high-speed steel may contain only 0.7% carbon, its microstructure exhibits masses of free carbide due to the displacement of the eutectoid point far to the left by the effects of the alloying elements which are present. Whilst Figure 4. shows the extent to which some elements raise or lower the eutectoid temperature. This latter will move in sympathy with the A_3 point.

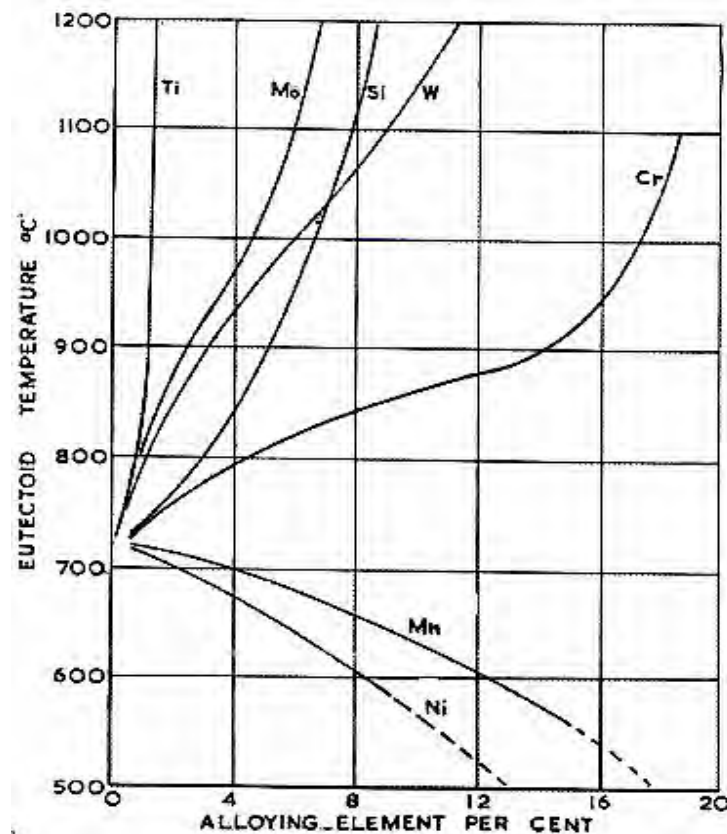


Figure 4. The effect of alloying elements on the eutectoid temperature.

5. The Retardation of Transformation Rates.

By adding alloying elements, we reduce the critical cooling rate which is necessary for the transformation of austenite to martensite to take place. This feature of the alloying of steels has obvious advantages and all alloying elements, with the exception of cobalt, will reduce transformation rates.

In order to obtain a completely martensitic structure in the case of a plain 0.83% carbon steel, we must cool it from above 723° C to room temperature in approximately one second. This treatment involves a very drastic quench, generally leading to distortion or cracking of the component. By adding small amounts of suitable alloying elements, such as nickel and chromium, we reduce this critical cooling rate to such an extent that a less drastic oil-quench is rapid enough to produce a totally martensitic structure. Further increases in the amounts of alloying elements will so reduce the rate of transformation that such a steel can be hardened by cooling in air.

"Air-hardening" steels have the particular advantage that comparatively little distortion is produced during hardening. This feature of alloying is one of the greatest significance.

6. The Improvement in Corrosion-resistance.

The corrosion-resistance of steels is substantially improved by the addition of elements such as aluminum, silicon and chromium. These elements form thin but dense and adherent oxide films which protect the surface of the steel from further attack.

7. Effects on the Mechanical Properties.

One of the main reasons for alloying is to effect improvements in the mechanical proper ties of a steel. These improvements are generally the result of physical changes already referred to.

For example:

hardness is increased by stabilising the carbides; strength is increased when alloying elements dissolve in the ferrite; and toughness is improved due to refinement of grain.

Some alloying elements may improve the magnetic properties such as cobalt and tungsten while other elements can made the alloy steel without any particles such as vanadium.

Some general effects of adding an alloying elements is shown in table 1:

Nickel Steel

Nickel is extensively used in alloy steels for engineering purposes, generally in quantities up to about 5.0%. When so used, its purpose is to increase tensile strength and toughness. It is also used in stainless steel. The main sources of nickel are the Sudbury mines in Northern Ontario, Canada; Cuba and the one-time cannibal island of New Caledonia in the Pacific.

The addition of nickel to a plain carbon steel tends to stabilize the austenite phase over an increasing temperature range, by raising the A_4 point and lowering the A_3 point. Thus, the addition of 25% nickel to pure iron renders it austenitic, and so non-magnetic, even after slow cooling to room temperature. The structure obtained after slow cooling to room temperature can be estimated for a nickel steel of known composition by referring to the type of diagram devised by **Guillet** (Figure 5). These diagrams show the approximate relationship between microstructure, carbon content and the amount of alloying element added.

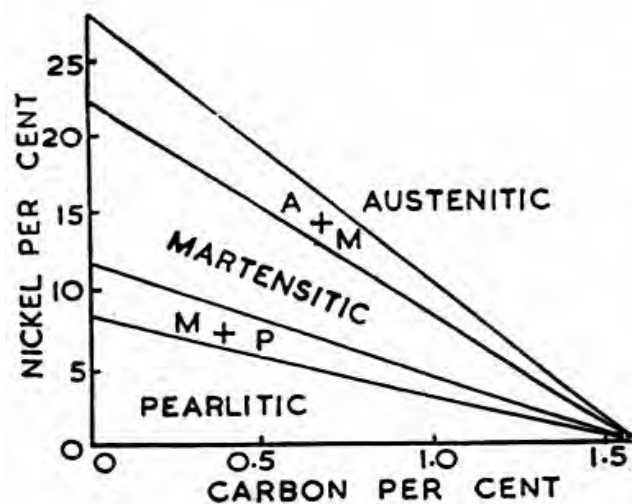


Figure 5. The Effects of Nickel as an Alloying Element of the Guillet diagram.

At the same time nickel makes the carbides unstable and tends to cause them to decompose to graphite. For this reason it is inadvisable to add nickel by itself to a high-carbon steel, and most nickel steels are low-carbon steels. If a higher carbon content is desired, then the manganese content is usually increased, since manganese acts as a stabiliser of carbides.

In addition to improving tensile strength and toughness, nickel has a grain-refining effect which makes the low-nickel, low-carbon steels very suitable for case-hardening, since grain growth will be limited during the prolonged period of heating in the region of 900° C.

The 3% and 5% nickel steels are the most widely employed. Those with the lower carbon contents are used mainly for case-hardening, whilst those with up to 0.4% carbon are used for structural purposes, shafting, gears, etc.

Chromium steels

The main producers of chromium are the South Africa, the Philippines, Jugoslavia, New Caledonia, Rhodesia, Cuba and Turkey, though not all of these countries are important exporters. Sierra Leone, a relatively small producer, is at present expanding its output.

The main function of chromium when added in relatively small amounts to a carbon steel is to cause a considerable increase in hardness. At the same time strength is raised with some loss in Ductility, though this is not noticeable when less than 1.0% chromium is added. The increase in hardness is due mainly to the fact that chromium is a carbide stabiliser, and forms the hard carbides Cr_7C_3 or Cr_{23}C_6 .

Chromium lowers the A_4 temperature and raises the A_3 temperature, forming the closed γ -loop already mentioned. In this way it stabilises the α -phase at the expense of the γ -phase. The latter is eliminated entirely, as shown in Figure 6, if more than 11% chromium is added to pure iron, though with carbon steels a greater amount of chromium would be necessary to have this effect.

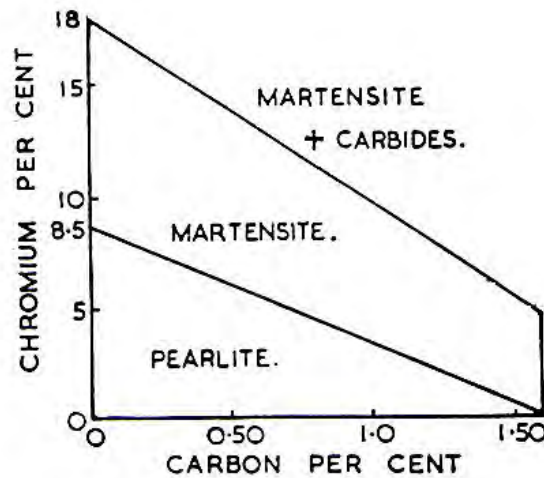


Figure 6. The Effects of Chromium as an Alloying Element.

The main disadvantage in the use of chromium as an alloying element is its tendency to promote grain growth, with the attendant brittleness that this involves. Care must therefore be taken to avoid overheating or holding for too long at the normal heat-treatment temperature.

Steels containing small amounts of chromium and up to 0.45% carbon are used for axle shafts, connecting-rods and gears; whilst those containing more than 1.0% carbon are extremely hard and are useful for the manufacture of ball-bearings, drawing dies and parts for grinding machines.

Chromium is also added in larger amounts up to 21% and has a pronounced effect in improving corrosion-resistance due to the protective layer of oxide formed. This oxide layer is extremely thin, and these steels take a very high polish. They contain little or no carbon and are therefore completely ferritic and non-hardening (except by cold-work). They are used widely in the chemical-engineering industry; for domestic purposes, such as stainless-steel sinks; and in food containers, refrigerator parts, beer barrels, cutlery and table-ware. The best-known alloy in this group is "stainless iron", containing 13% chromium and usually less than 0.05% carbon.

If the carbon content exceeds 0.1% the alloy is a true *stainless steel* and is amenable to hardening by heat treatment. The most common alloy in this group contains 13% chromium and approximately 0.3% carbon. Due to displacement of the eutectoid point to the left, this steel is of approximately eutectoid composition. It is widely used in stainless-steel knives.

Nickel - Chromium Steels

Certain *disadvantages* attend the addition of either nickel or chromium, singly, to a carbon steel. Whilst nickel tends to prevent grain growth during heat-treatment, chromium accelerates it, producing

the attendant brittleness under shock. On the other hand, whilst chromium tends to form stable carbides, making it possible to produce high-chromium, high-carbon steels, nickel has the reverse effect in assisting graphitisation. The deleterious effects of each element can be overcome, therefore, if we add them in conjunction with each other. Then, the tendency of chromium to cause grain growth is nullified by the grain-refining effect of the nickel, whilst the tendency of nickel to favor graphitisation of the carbides is counteracted by the strong carbide-forming tendency of the chromium.

At the same time other physical effects of each element are additive, so that they combine in:

- increasing strength,
- corrosion-resistance
- the retardation of transformation rates during heat-treatment.
- heat resistance
- increase and stability of carbides that leads to increase in the hardness.
- making the drastic water-quenches avoidable.

These advantages make the Ni – Cr steels used at very important fields such as : stations of electricity generation, the tools of surgery , valves, the tools of cooking and it is etc.

Engineering Materials

10

Metal Cutting

Introduction :

Before the middle of the 18th century the main material used in engineering structures was wood. The lathe and a few other machine tools existed, mostly constructed and most commonly used for shaping wooden parts. The boring of cannon and the production of metal screws and small instrument parts were the exceptions. It was the steam engine, with its requirement of large metal cylinders and other parts of unprecedented dimensional accuracy, which led to the first major developments in metal cutting.

The materials of which the first steam engines were constructed were not very difficult to machine. Grey cast iron, wrought iron, brass and bronze were readily cut using hardened carbon steel tools. The methods of heat treatment of tool steel had been evolved by centuries of craftsmen, and reasonably reliable tools were available. Although rapid failure of the tools could be avoided only by cutting very slowly.

The technology of metal cutting has been improved by contributions from all the branches of industry with an interest in machining. The replacement of carbon tool steel by high speed steels and cemented carbides has allowed cutting speeds to be increased by many times. Machine tool manufacturers have developed machines capable of making full use of the new tool materials, while automatic machines, numerically controlled (NC) machines, often with computer control (CNC), and transfer machines greatly increase the output per worker employed. Tool designers and machinists have optimized the shapes of tools to give long tool life at high cutting speed. Lubricant manufacturers have developed many new coolants and lubricants to improve surface finish and permit increased rates of metal removal.

Progress in technology of machining is achieved by the ingenuity and experiment, logical thought and dogged worrying of many thousands of practitioners engaged in the many-sided arts of metal cutting. The worker operating the machine, the tool designer, the lubrication engineer, the

metallurgist, are all constantly probing to find answers to new problems created by the necessity to machine novel materials, and by the incentives to reduce costs, by increasing rates of metal removal, and to achieve greater precision or improved surface finish.

During cutting, the interface between tool and work material is largely inaccessible to observation, but indirect evidence concerning stresses, temperatures, metal flow and interactions between tool and work material

While heat can be made to fuse and unite, it can also be employed to separate, that is, perform a cutting operation. The earliest arc welding patent for the Benardos carbon-arc process also mention cutting. This was achieved by forming a molten pool and allowing it to fall out by gravity.

The results of thermal cutting in this way are rough and generally unsatisfactory but great improvements result from combining the heat source with a jet of gas, usually oxygen or air.

- ❖ An air jet with a carbon arc is widely used for gouging the surface of steel. The arc melts a pool on the surface and the air jet blows it away.
- ❖ An oxygen jet with an oxy-acetylene heat source was the most commonly used thermal cutting process for steel. Although today oxy-propane has become widely used.
- ❖ In plasma cutting an inert gas tungsten arc is constricted by making the arc pass through a water-cooled nozzle and the inert gas thus concentrated forms the jet which ejects the molten metal from the cut.
- ❖ A recent development has allowed air to be used the plasma torch for cutting thin sheet steel. This has only been possible by finding an electrode material more resistant to oxidation than tungsten.
- ❖ Most cutting processes, including oxy-fuel gas cutting, are available with computer controlled profiling equipment which can access standard shapes in memory and select the sequence of cutting and the arrangement of shapes to provide the most economical use of material.

There are different types of metal cutting process, we will study the following three types as an example of the materials used for cutting:

1) Cutting with the oxy-fuel gas

The oxy-fuel gas cutting process depends on the reaction between oxygen and iron to form iron oxides. This reaction gives out considerable heat and is self-sustaining once the required preheat or 'kindling' temperature is reached. To carry out cutting a blowpipe is needed in which the nozzle supplying the oxy-fuel gas flame contains a central orifice through which a jet of oxygen can be directed. Actually the preheating flame is usually supported from a ring of holes as shown in figure 1.

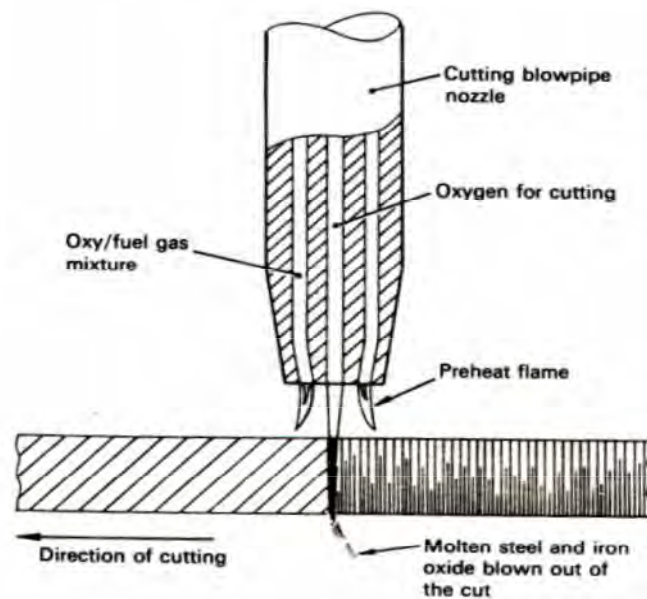


Figure 1. Principle of oxy-fuel gas cutting.

Cutting then commences with the flow of oxygen sweeping away the fluid products of combustion through the slot which is being cut. The slot is called a **kerf**. Oxy-fuel gas cutting is sensitive to the cleanliness of the surface being cut and if possible rust or paint should be removed before cutting begins.

Manual oxy-fuel gas cutting is extremely useful for reclaiming scrap metal and fettling castings, etc. Although manual cutting is used on a small scale for preparing edges for welding the quality of the cut is greatly improved by mechanisation. A major use of oxy-fuel gas cutting is in mechanised or automated cutting.

2) Laser cutting

Laser cutting was the first and still is the most important application for CO₂ lasers up to 500W. It is normally carried out with the aid of a gas jet, as shown in figure 2, oxygen or compressed air being used for ferrous materials (as the resultant exothermic reaction assists the cutting process) and inert gases when cutting non-metals. The process will cut profiles with precision at high speed and is especially suitable for heat resisting and alloy steels which are difficult to cut by other means.

For example: Cutting speeds for mild steel with a 500 W laser are indicated by the rule-of-thumb:

Steel thickness	mm	1	2	3	4	$\frac{in}{1000}$	40	80	120	160
Cutting speed	m/min	4	3	2	1	ipm	160	120	80	40

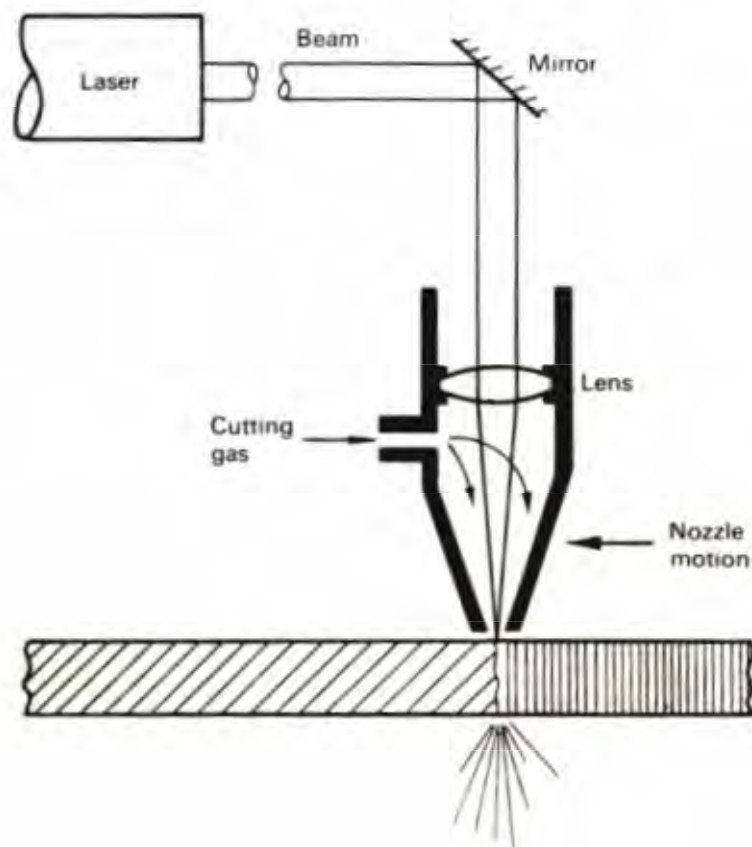


Figure 2. Principle of laser cutting.

- 3) some materials used for cutting such as **diamond** which is the hardest of all materials, diamond, has long been employed as a cutting tool although its high cost has restricted use to operations where other tool material cannot perform effectively. Diamond tools show a much lower rate of wear and longer tool life than carbides or oxides under conditions where abrasion is the dominant wear mechanism because of their very high hardness. The extreme hardness of diamond is related to its crystal structure. This consists two interpenetrating, face-centered cubic lattices arranged so that each carbon atom has four near neighbors to which it is attracted by covalent bonds.

Importance of Coolants and lubricants in cutting of materials:

A tour of most machine shops will demonstrate that some cutting operations are carried out dry, but in many other cases, a flood of liquid is directed over the tool, to act as a coolant and or a lubricant. These cutting fluids perform a very important role and many operations cannot be efficiently carried out without the correct type of fluid. They are used for a number of objectives:

- (1) To prevent the tool, work piece and machine from overheating.
- (2) To increase tool life.
- (3) To improve surface finish.
- (4) To help clear the swarf from the cutting area.

Engineering Materials

11

Non-Ferrous Materials

Introduction :

The non-ferrous metals which are most commonly used by engineers, it also refers to the 38 metals other than iron that are known to man.

Two of the most important non-ferrous metals are Aluminum (Al) and Copper (Cu). They are not only form the bases of many important alloys, but they are widely used in their own right as pure metals.

A list of non-ferrous metals would be complete without mention of the '**new metals**'. Although known for many years, these metals have only been available in bulk for engineering applications since the Second World War. Further with the development of supersonic aircraft and the nuclear power industry, that there has been a large – scale commercial demand for these materials.

These 'new metals' are very expensive compared with the more conventional engineering materials and they are only used where their special properties can be fully exploited.

The pure non-ferrous metals are used mainly where their properties of corrosion resistance and high electrical and thermal conductivity can be exploited. They are not widely used as structural materials in mechanical engineering because of their relatively low strengths.

Aluminum and Its Alloys

Introduction :

The first samples of aluminum was produced in 1825 by the Danish physicist and chemist H.C. Oersted.

While in 1886 a C.M. Hall had discovered a relatively cheap method for producing aluminum by electrolyzing a fused mixture of aluminum oxide and the mineral cryolite.

Aluminum cannot be purified by blowing air through it, as in the case of iron. This treatment would oxidise the aluminum and leave behind the impurities. Therefore the ore must be purified before being electrolysed, and this, involves an expensive chemical process. Although aluminum has a great affinity for oxygen, its corrosion-resistance is relatively, high. This is due to the dense impervious film of oxide which forms on the surface of the metal and protects it from further oxidation. The high affinity of aluminum for oxygen also makes it useful as a deoxidant in steels and also in the Thermit process of welding.

The properties of aluminum which chiefly affect its use as a metallurgical material are its low relative density and its high affinity for oxygen. Since its relative density is only about one-third that of steel, or of a copper-base alloy, it is used, when alloyed with small amounts of other elements, for castings in aero, automobile and constructional engineering. Moreover, alloying and heat-treatment can produce alloys of aluminum which are, weight for weight, stronger than steel, so that the use of aluminum alloys is further extended to stress-bearing members in both aero-engine and air-frame.

The fact that aluminum has over 50% of the specific conductivity of copper means that, weight for weight, it is a better conductor of electricity than is copper. Hence it is now widely used, generally twisted round a steel core for strength, as a current carrier in the electric "grid" system. Pure aluminum is relatively soft and weak (it has a tensile strength of about 90 N/mm^2 in the annealed condition), so that for most other engineering purposes it is used in the alloyed condition.

Alloys of Aluminum

The addition of alloying elements is made principally to improve mechanical properties, such as tensile strength, hardness, rigidity and machinability, and sometimes to improve fluidity and other casting properties.

One of the chief defects to which aluminum alloys are prone is porosity due to gases dissolved during the melting process. Molten Aluminum will dissolve considerable amounts of hydrogen if, for any reason, this is present in the furnace atmosphere. When the metal is cast and begins to solidify the solubility of hydrogen diminishes almost to zero, so that tiny bubbles of gas are formed in the partly solid metal. These cannot escape, and give rise to "pinhole" porosity. The defect is eliminated by treating the molten metal before casting with a suitable "flux, or by bubbling nitrogen or chlorine through the melt. As a substitute for chlorine, which is a poisonous gas, tablets of the organic compound hexachlorethane can be used.

Aluminum alloys are used in both the cast and wrought conditions. Whilst the mechanical properties of many of them, both cast and wrought, can be improved by the process known as "**precipitation-hardening**", a number are used without any such treatment being applied. It is convenient, therefore, to classify the somewhat bewildering multitude of aluminum alloys into the following two main groups, according to the condition in which they are employed.

1. Wrought Alloys

a) Wrought alloys which are not heat – treated:

The main requirements of alloys in this group are sufficient strength and rigidity in the work-hardened state, coupled with good corrosion-resistance. As will be seen, these alloys are widely used in the manufacture of panels for land-transport vehicles. Here the high corrosion – resistance of the aluminum - magnesium alloys is utilized, those with a higher magnesium value having an excellent resistance to sea-water and marine atmospheres, so that they are used extensively for marine super - structures. The desired mechanical properties are produced by the degree of cold-work applied in the final cold-working operation and these alloys are commonly supplied as "soft", "quarter hard" , "half hard", "three-quarter hard" or "full hard". The main disadvantage is that,

once the material has been finished to size, no further variation can be made in mechanical properties (other than softening by annealing), whereas, with the precipitation-hardening alloys, the properties can be varied, within limits, by heat-treatment.

b) Wrought alloy which are heat – treated:

The most significant feature of the aluminum alloys is the ability of some of them to undergo a change in properties under suitable heat-treatment. Although this phenomenon is not confined to aluminum alloys, but is possible with any alloy in a series in which change in solubility of some constituent in the parent metal takes place, it is more widely used in the aluminum-base alloys than in any others.

The phenomenon was first observed by a German research metallurgist, **Dr. Alfred Wilm**, in 1906, who noticed that an aluminum alloy containing small amounts of magnesium, silicon and copper, when quenched from a temperature in the region of 500° C, subsequently hardened unassisted, if allowed to remain at room temperature over a period of days.

The strength increased in this way, reaching a maximum value in just under a week, and the effect was subsequently known as "**age-hardening**". About four years later Wilm transferred the sole rights of his patent to the Duren Metal Works at Duren in Western Germany, and the alloy produced was named "**duralumin**".

The first significant use of duralumin was during the First World War, when it found application in the structural members of the airships bearing the name "Graf von Zeppelin".

The age-hardening process can be accelerated by heating the quenched alloy at temperatures up to 180° C. Such treatment was referred to originally as "**artificial age-hardening**", but both of these lightly misleading titles are now covered in modern metallurgical nomenclature by the general term "**precipitation-hardening**".

We will consider the application of this principle to the precipitation-hardening of aluminum-copper alloys.

Let us assume that we have an aluminum-copper alloy containing 4.0 % copper. At temperatures above 500° C this will consist entirely of a solid solution as indicated by the equilibrium diagram figure 1. If we now allow the alloy to cool *very slowly* to room temperature, equilibrium will be reached at each stage and particles of the inter metallic compound CuAl_2 (θ) will form as a non-coherent precipitate. This precipitation will commence at *A* and continue until at room temperature only 0.2% (X) copper remains in solution in the aluminum. The resulting structure will lack strength because only 0.2% copper is left in solution, and it will be brittle because of the presence of coarse particles of CuAl_2 .

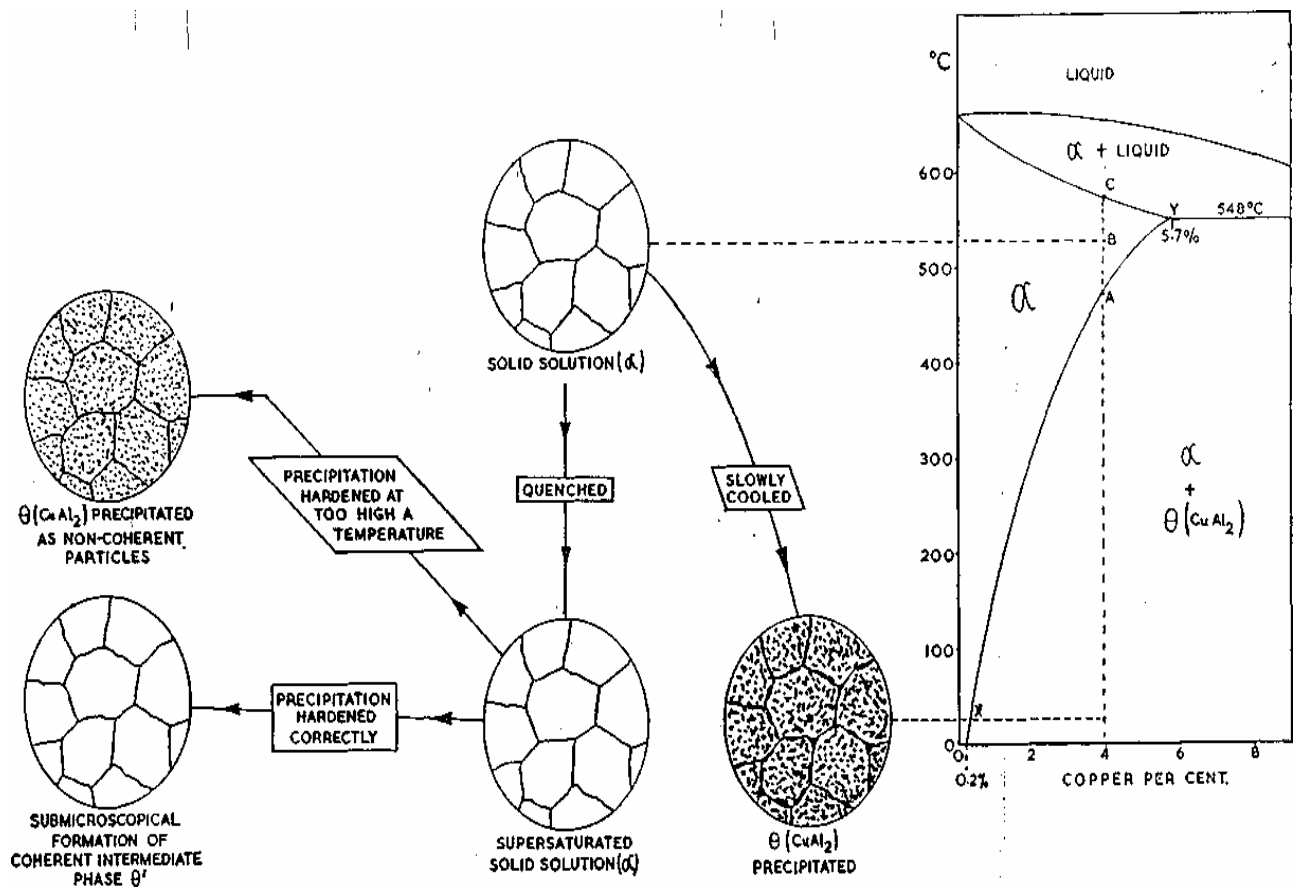


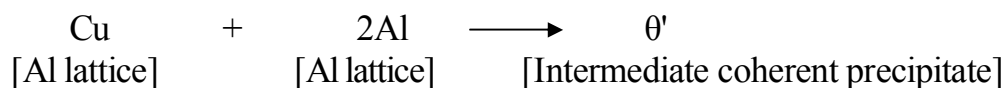
Figure 1. Aluminum-rich end of the Aluminum-Copper equilibrium diagram, showing the observed microstructure effects of slow cooling and precipitation-hardening.

If the alloy is now slowly reheated, the particles of CuAl_2 will be gradually absorbed, until at *A* we once more have a complete solid solution α (in industrial practice a slightly higher temperature, *B*, will

be used to ensure complete solution of the CuAl_2). On quenching the alloy we retain the copper in solution, and, in fact, produce a supersaturated solution of copper in aluminum at room temperature.

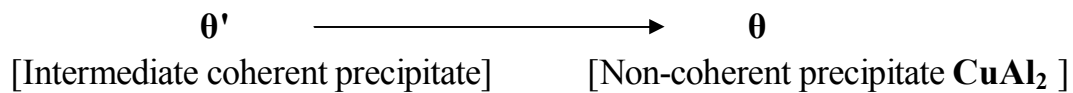
In this condition the alloy is somewhat stronger and harder because there is more copper actually in solid solution in the aluminum, and it is also much more ductile, because the brittle particles of CuAl_2 are now absent. So far these phenomena permit of a straightforward explanation, forthcoming from a simple study of the microstructure. What happens subsequently is of a sub-microscopical nature, that is, its observation is beyond the range of an ordinary optical microscope.

If the quenched alloy is allowed to remain at room tempera-> it will be found that strength and hardness gradually increase (with corresponding reduction in ductility) and reach a maximum in about six days. After this time has elapsed no further appreciable changes occur in the properties. The completely α -phase structure obtained by quenching is not the equilibrium structure at room temperature. It is in fact super-saturated with copper so that there is a strong urge for copper to be rejected from the solid solution α as particles of the non-coherent precipitate CuAl_2 (θ). This stage is never actually reached at room temperature because of the sluggishness of diffusion of the copper atoms within the aluminum lattice. However, some movement does occur and the copper atoms take up positions within the aluminum lattice so that nuclei of the intermediate phase (θ') are formed. These nuclei are present as a coherent precipitate *continuous* with the original α lattice, and in this form, cause distortion within the α lattice. This effectively hinders the movement of dislocations and so the yield strength is increased. The sub-microscopical change within the structure can be represented so:



An improvement in properties over those obtained by ordinary "natural age-hardening" can be attained by "tempering" the quenched alloy at temperatures up to nearly 200° C for short periods. This treatment increases the amount of the intermediate coherent precipitate θ' by accelerating the rate of diffusion, and so strength and hardness of the alloy rise still further. If the alloy is heated to a higher temperature, a stage is reached where the structure begins to revert

rapidly to one of equilibrium and the coherent intermediate phase θ' precipitates fully as non-coherent particles of θ (CuAl_2):



When this occurs both strength and hardness begin to fall. Further increases in temperature will cause the θ particles to grow to a size making them easily visible with an ordinary optical microscope, and this will be accompanied by a progressive deterioration in mechanical properties. Figure 2 illustrates the general effects of variations in time and temperature during post-quenching treatment for a typical alloy of the precipitation-hardening variety. At room temperature (20°C) the tensile strength increases slowly and reaches a maximum of about 390 N/mm^2 . Precipitation-treatment at temperatures above 100°C will result in a much higher maximum tensile strength being reached. Optimum strength is obtained by Treatment at 165°C for about ten hours, after which, if the treatment time is prolonged, rapid precipitation of non-coherent particles of θ (CuAl_2) will cause a deterioration in tensile strength and hardness as shown by curve C. Treatment at 200°C , as represented by curve D, will give poor results because the rejection from solution of non-coherent θ is very rapid such that precipitation will "overtake" any increase in tensile strength. This process of deterioration in structure and properties due to faulty heat-treatment is generally termed "reversion". Time and temperature of precipitation-treatment differ with the composition of the alloy, and must always be controlled accurately to give optimum results.

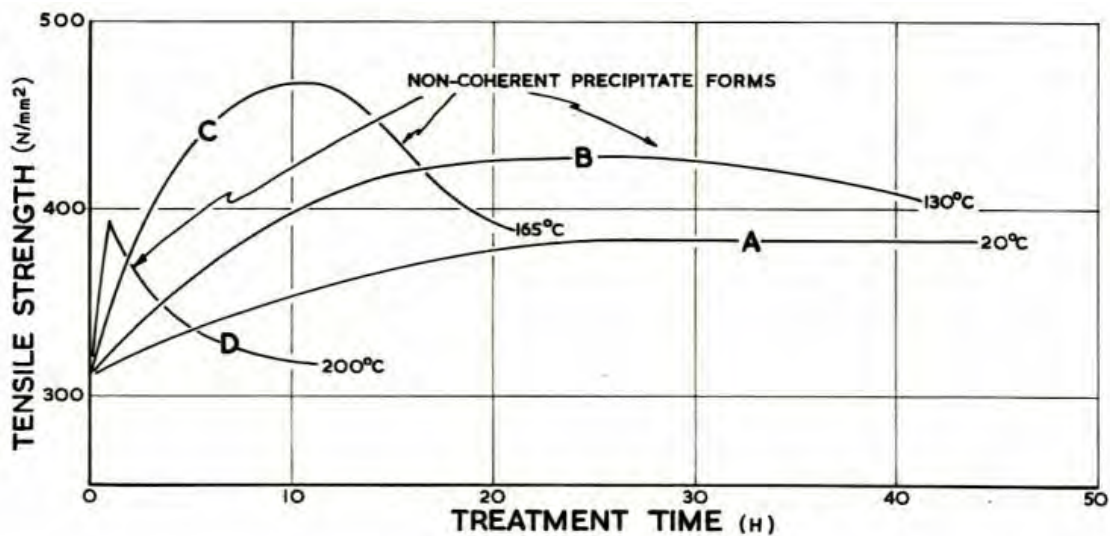


Figure 2. The effects of time and temperature of participation –treatment on the structure and tensile strength of a suitable alloy.

There are a number of alloy compositions sold under the general trade name of "**Duralumin**", but all of them rely on the presence of approximately 4.0% copper to effect hardening. In addition, both Magnesium and silicon are usually present, so that hardening will to some extent be assisted by the formation of Mg_2Si . Thus, one standard grade of duralumin contains 4.0% copper, 0.6% manganese, 0.5% magnesium and 0.4% silicon, with small amounts of iron. The main function of manganese is to refine the grain.

Just as "**tempering**" will accelerate precipitation-hardening, so will refrigeration impede the process. This fact was utilised extensively in aircraft production during the Second World War. If a duralumin rivet is solution-treated it is in a soft condition, but if sufficient time is allowed to elapse before using the solution-treated rivet it will begin to harden and will possibly split whilst being driven. It was found that if, immediately after quenching, the duralumin rivets were stored in a refrigerator at about $-20^\circ C$, precipitation-hardening was considerably slowed down, and the rivets could therefore be stored at the sub-zero temperature until they were required.

Although the addition of copper forms the basis of many of the precipitation-hardening aluminum alloys, copper is absent from a number of them which rely instead on the presence of magnesium

and silicon. Such alloys have a high electrical conductivity approaching that of pure aluminum, so that they can be used for the manufacture of overhead conductors of electricity. Most commercial grades of aluminum contain iron as an impurity, but in some of these alloys it is utilised in greater amounts in order to increase strength by promoting the formation of FeAl_3 , which assists in precipitation-hardening. Titanium finds application as a grain refiner, whilst other alloys containing zinc and chromium produce tensile strengths in excess of 620 N/mm^2 in the heat-treated condition.

2. Casting Alloys

a) Cast alloys which are not heat-treatment

This group of alloys contain those which are widely used as general-purpose materials as sand-casting. These alloys are mainly used when rigidity, fluidity in casting and good corrosion-resistance are important than strength. Undoubtedly the most widely used alloys in this class are those containing between 9 and 13 % silicon, with occasionally small amounts of copper.

b) Cast alloys which are heat-treatment

Many of these alloys are of the 4 % copper type, whilst others contain an addition of about 2 % nickel. Precipitation-hardening is then due to the combined effects of intermediate phases based on the intermetallic compounds CuAl_2 and NiAl_3 .

As a cast alloy it is used where high strength is required at elevated temperatures, as, for example, in high duty piston and cylinder heads.

Copper and Its Alloys

Introduction :

Copper was undoubtedly the first metal to be used by Man. In many countries it is found in small quantities in the metallic state and, being soft, it was readily shaped into ornaments and utensils.

It is thought that bronze was accidentally produced in Cornwall by smelting ores containing both tin- and copper-bearing minerals in the camp fires of ancient Britons. It was the best material for making knives and other cutting implements.

Properties and Uses of Copper

A very large part of the world's production of metallic copper is used in the unalloyed form, mainly in the electrical industries. Copper has a very high specific conductivity, and is, in this respect, second only to silver, to which it is but little inferior. When relative costs are considered, copper is naturally the metal used for industrial purposes demanding high electrical conductivity.

1) The Electrical Conductivity of Copper.

The International Standard of Electrical Resistance for annealed copper was adopted in 1913 and copper which reached this standard was said to be 100% conductive. The fact that, working to the 1913 standard, figures of 101 and 102% are frequently quoted is explained by reason of improvements that have taken place in the production of copper since 1913.

As indicated in Figure 3, the presence of impurities reduces electrical conductivity. To a less degree, cold-work has the same effect. Reduction in conductivity caused by the presence of some elements in small amounts is not great, so that up to 1% cadmium, for example, is added to telephone wires in order to strengthen them. Such an alloy, when hard-drawn, has a tensile strength of some 460 N/mm^2 as compared with 340 N/mm^2 for hard-drawn, pure copper, whilst the electrical conductivity is still over 90% of that for soft pure copper. Other elements have pronounced effects on conductivity; 0.04% phosphorus, for

example, will reduce the electrical conductivity to about 75% of that for pure copper.

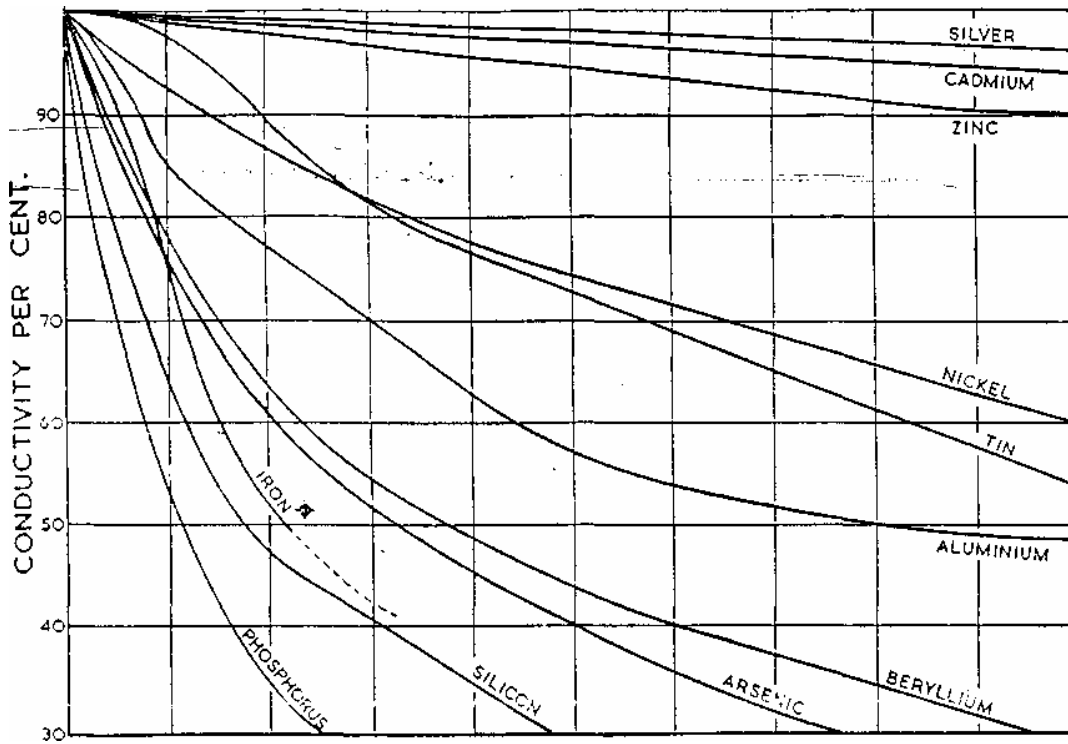


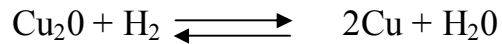
Figure 3. The Effect of Impurities on the Electrical Conductivity of Copper.

2) The Commercial Grades of Copper

It include both furnace-refined and electrolytically refined metal. High-conductivity copper (usually referred to as O.F.H.C. or "oxygen-free high conductivity") is of the highest purity, and contains at least 99-99% copper. It is used where the highest electrical and thermal conductivities are required, and is copper which has been refined electrolytically.

Fire-refined grades of copper can be either "tough pitch" or "deoxidised" according to their subsequent application. The former contains small amounts of oxygen (present as cuprous oxide, Cu_2O) absorbed during the manufacturing process. It is usually present in amounts of the order of 0.04-0.05% oxygen (equivalent to 0.45- 0.55% cuprous oxide). The cuprous oxide is present as tiny globules, which are part of a copper-cuprous oxide eutectic. These globules have a negligible effect as far as electrical conductivity, and most of the other properties, are concerned.

For processes such as welding and tube-making, however, the existence of these globules is extremely deleterious, since reducing atmospheres containing hydrogen cause "gassing" of the metal. Hydrogen is soluble in solid copper, so that it comes into contact with the subcutaneous globules of cuprous oxide, reducing them thus:



Although this is what is called a "reversible reaction", the high concentration of hydrogen relative to cuprous oxide makes the reaction proceed to the right, and the water formed is present as steam, which is almost insoluble in solid copper. It is therefore precipitated at the crystal boundaries, thus, in effect, pushing the crystals apart and reducing the ductility by as much as 85% and the tensile strength by 30 - 40%. Under the microscope "gassed" tough-pitch copper is recognised by the thick grain boundaries, which are really minute fissures, and by the absence of cuprous oxide globules.

For such purposes as welding, therefore, copper is deoxidised before being cast by the addition of phosphorus, which acts in the same way as the manganese used in deoxidising steels. A small excess of phosphorus, of the order of 0.04%, dissolves in the copper after deoxidation, and this small amount is sufficient to reduce the electrical conductivity by as much as 25%. So, whilst copper which is destined for welding or thermal treatment in hydrogen-rich atmospheres should be of this type, copper deoxidised by phosphorus would be unsuitable for electrical purposes, where either electrolytic copper or good-quality tough-pitch copper must be used.

Up to 0.5% arsenic was added to much of the copper used in the construction of locomotives. This addition considerably increased the strength at elevated temperatures by raising the softening temperature from about 190° C for the pure metal to 550° C for arsenical copper. This made arsenical copper useful in the manufacture of steam locomotive fire-boxes, boiler tubes and rivets, since the alloy, whilst being stronger at high temperatures, still had a high thermal conductivity.

The addition of 0.5 % lead or tellurium imparts free-cutting properties to copper and provides a material which can be machined

to close tolerances whilst still retaining 95% of the conductivity of pure copper.

3) The Effects of Impurities

The Effects of Impurities on the electrical properties of copper have already been mentioned. Quite small amounts of some impurities will also cause serious reductions in the mechanical properties.

Bismuth is possibly the worst offender, and even as little as 0.002% will sometimes cause trouble, since bismuth is insoluble in amounts in excess of this figure, and, like ferrous sulphide in steel, collects as brittle films at the crystal boundaries. Antimony produces similar effects and, in particular, impairs the cold-working properties.

Selenium and tellurium make welding difficult, in addition to reducing the conductivity and cold-working properties; whilst lead causes hot-shortness, since it is insoluble in copper and is actually molten at the hot-working temperatures.

The Copper-base Alloys

The copper-base alloys include the **brasses** and **bronzes**, the latter being copper-rich alloys containing either tin, aluminum, silicon or beryllium; though the tin bronzes are possibly the best known.

☉ The Brasses

The brasses comprise the useful alloys of copper and zinc containing up to 45% zinc, and constitute one of the most important groups of non-ferrous engineering alloys.

As shown by the equilibrium diagram figure 4, copper will dissolve up to 32.5% zinc at the solidus temperature of 902° C, the proportion increasing to 39.0% at 454° C. With extremely slow rates of cooling, which allow the alloy to reach structural equilibrium, the solubility of zinc in copper will again decrease to 35.2% at 250° C. Diffusion is very sluggish, however, at temperatures below 450° C, and with ordinary industrial rates of cooling the amount of zinc which can remain in solid solution in copper at room temperature is about 39%. The solid solution so formed is represented by the symbol α . Since this solid solution is of the disordered type, it is prone to the phenomenon of coring, though this is not extensive, indicated by the

narrow range between liquids and solidus.

If the amount of zinc is increased beyond 39 % another phase, β' , will appear in the microstructure of the slowly cooled brass. This phase is hard, but quite tough at room temperature, and plastic when it changes to its modification β above 454° C. Further increases in the zinc content beyond 50 % cause the appearance of the phase γ in the structure. This is extremely brittle, rendering alloys which contain it unsuitable for engineering purposes.

Due to coring effects, an alloy which is nominally α -phase in structure may contain some β' - phase in the as-cast condition. This will depend upon the rate of cooling and the nearness of the composition of the alloy to the $\alpha / \alpha + \beta'$ phase boundary. Such β' -phase will usually be absorbed fairly quickly on subsequent mechanical working whilst hot. The $\alpha + \beta'$ alloys usually have a Widmanstatten structure on cooling, due to the manner in which the particles of the α -phase precipitate as the alloy cools from out of the β -phase area.

As mentioned above, the α -phase is quite soft and ductile at room temperatures, and for this reason the completely α -phase brasses are excellent cold-working alloys. The presence of the β' -phase, however, makes them rather hard and with a low capacity for cold-work; but since the β -phase is plastic at red heat, the $\alpha + \beta'$ brasses are best shaped by hot-working processes, such as forging or extrusion. The α -phase tends to be rather hot-short within the region of 30% zinc and between the temperatures of 300 and 750° C, and is therefore much less suitable as a hot-working alloy unless temperatures and working conditions are strictly controlled. The α -phase would also introduce difficulties during the extrusion of the $\alpha + \beta'$ alloys were it not for the fact that it is absorbed into the β -phase when the 60-40 composition (one of the most popular alloys of this group) is heated to a point above the $\alpha + \beta / \beta$ phase boundary in the region of 750° C, thus producing a uniform plastic structure of β -phase only. The α -phase is usually in process of being precipitated whilst hot-working is taking place, so that, instead of the Widmanstatten structure being formed again as the temperature tails, it is replaced by a refined granular $\alpha + \beta'$ structure which possesses superior mechanical properties to those of the directional Widmanstatten structure. The needle-shaped crystals of the α -phase are prevented from forming by the mechanical disturbances which

accompany the working process.

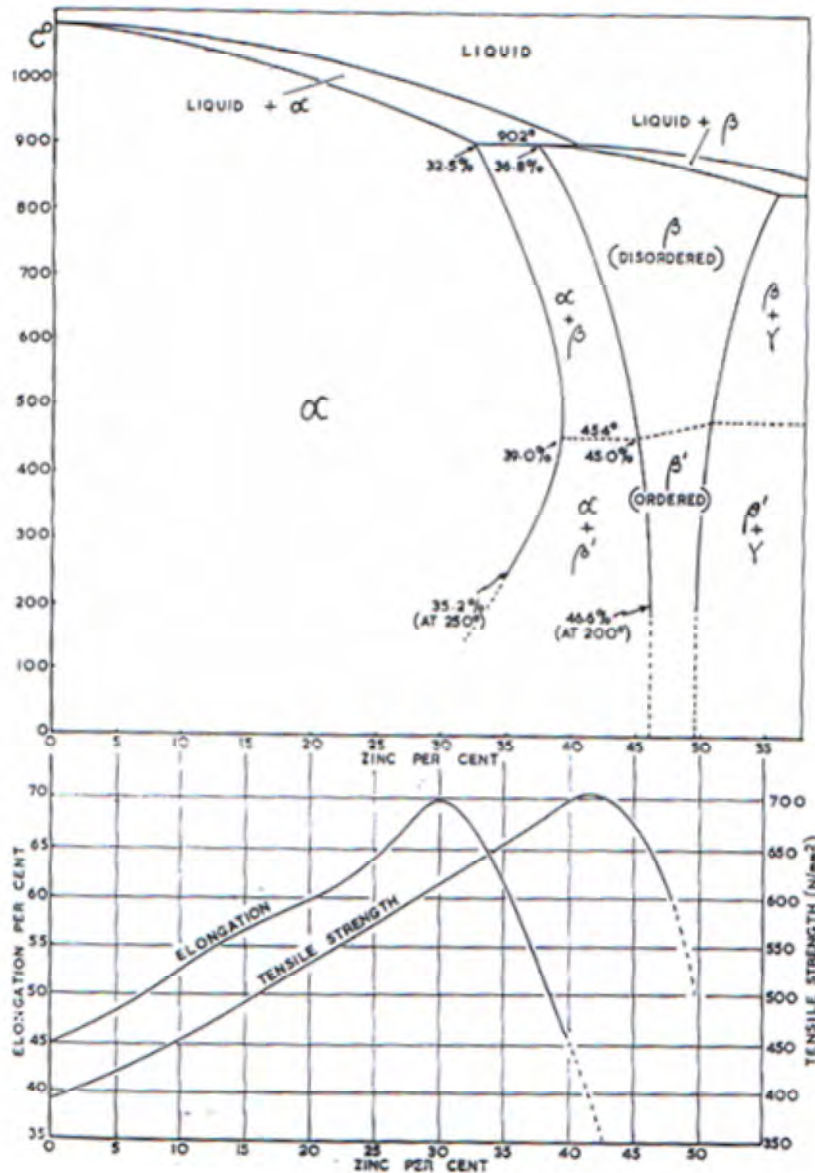


Figure 4. The Copper-Zinc Thermal-equilibrium Diagram. The lower diagram indicates the relationship between composition and mechanical Properties.

Thus the brasses can conveniently be classified according to whether they are hot-working or cold-working alloys.

⊕ **The Tin Bronzes**

Bronzes containing approximately 10 % Tin were probably the first alloys to be used by man. One of the significant factors in the early Roman conquests was undoubtedly the bronze sword, and it is thought that in even earlier times metal-workers realized that a high Tin content, in the region of 10 % produced a hard bronze whilst less Tin gave a softer alloy.

Engineering Materials

12

Polymers & Plastics

Introduction :

Naturally occurring polymers—those derived from plants and animals have been used for many centuries; these materials include wood, rubber, cotton, wool, leather, and silk. Other natural polymers such as proteins, enzymes, starches, and cellulose are important in biological and physiological processes in plants and animals.

Modern scientific research tools have made possible the determination of the molecular structures of this group of materials, and the development of numerous polymers, which are synthesized from small organic molecules. Many of our useful plastics, rubbers, and fiber materials are synthetic polymers. In fact, since the conclusion of World War II, the field of materials has been virtually revolutionized by the advent of synthetic polymers. The synthetics can be produced inexpensively, and their properties may be managed to the degree that many are superior to their natural counterparts. In some applications metal and wood parts have been replaced by plastics, which have satisfactory properties and may be produced at a lower cost.

To understand the polymers structure we should see first the **Hydrocarbon Molecules**. Since most polymers are organic in origin, we briefly review some of the basic concepts relating to the structure of their molecules. First, many organic materials are *hydrocarbons*; that is, they are composed of hydrogen and carbon. Furthermore, the intermolecular bonds are covalent. Each carbon atom has four electrons that may participate in covalent bonding, whereas every hydrogen atom has only one bonding electron. A single covalent bond exists when each of the two bonding atoms

contributes one electron, as represented schematically in Figure 1 for a molecule of methane (CH₄). Double and triple bonds between two carbon atoms involve the sharing of two and three pairs of electrons, respectively.

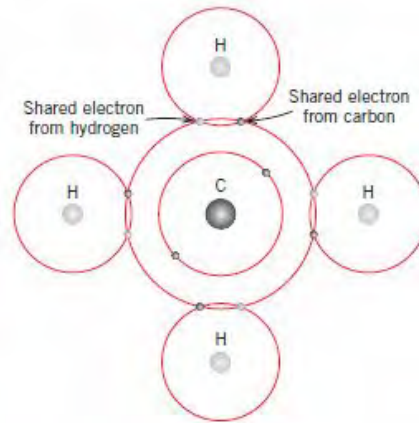
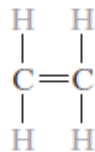
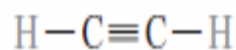


Figure 1. Schematic representation of covalent bonding in a molecule of methane (CH₄).

For example, in ethylene, which has the chemical formula C₂H₄, the two carbon atoms are doubly bonded together, and each is also singly bonded to two hydrogen atoms, as represented by the structural formula



where — and = denote single and double covalent bonds, respectively. An example of a triple bond is found in acetylene, C₂H₂:

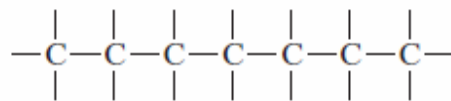


Molecules that have double and triple covalent bonds are termed **unsaturated**. That is, each carbon atom is not bonded to the maximum (four) other atoms; as such, it is possible for another atom or group of atoms to become attached to the original molecule. Furthermore, for a **saturated** hydrocarbon, all bonds are single ones, and no new atoms may be joined without the removal of others that are already bonded.

Polymer Molecules:

The molecules in polymers are gigantic in comparison to the hydrocarbon molecules already discussed; because of their size they are often referred to as **macromolecules**.

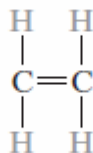
Within each molecule, the atoms are bound together by covalent interatomic bonds. For carbon chain polymers, the backbone of each chain is a string of carbon atoms. Many times each carbon atom singly bonds to two adjacent carbon atoms on either side, represented schematically in two dimensions as follows:



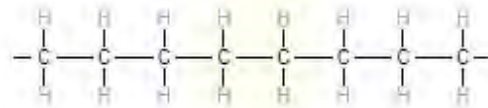
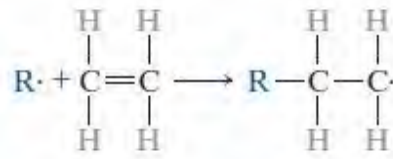
Each of the two remaining valence electrons for every carbon atom may be involved in side-bonding with atoms or radicals that are positioned adjacent to the chain. Of course, both chain and side double bonds are also possible. These long molecules are composed of structural entities called **repeat units**, which are successively repeated along the chain.¹ The term **monomer** refers to the small molecule from which a polymer is synthesized. Hence, monomer and repeat unit mean different things, but sometimes the term monomer or monomer unit is used instead of the more proper term repeat unit.

The Chemistry of Polymer Molecules:

Consider again the hydrocarbon ethylene (C_2H_4), which is a gas at ambient temperature and pressure, and has the following molecular structure:

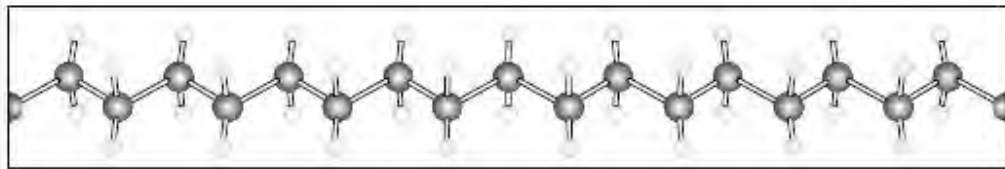


If the ethylene gas is reacted under appropriate conditions, it will transform to polyethylene (PE), which is a solid polymeric material. This process begins when an active center is formed by the reaction between an initiator or catalyst species () and the ethylene monomer, as follows:



Repeat unit

(a)

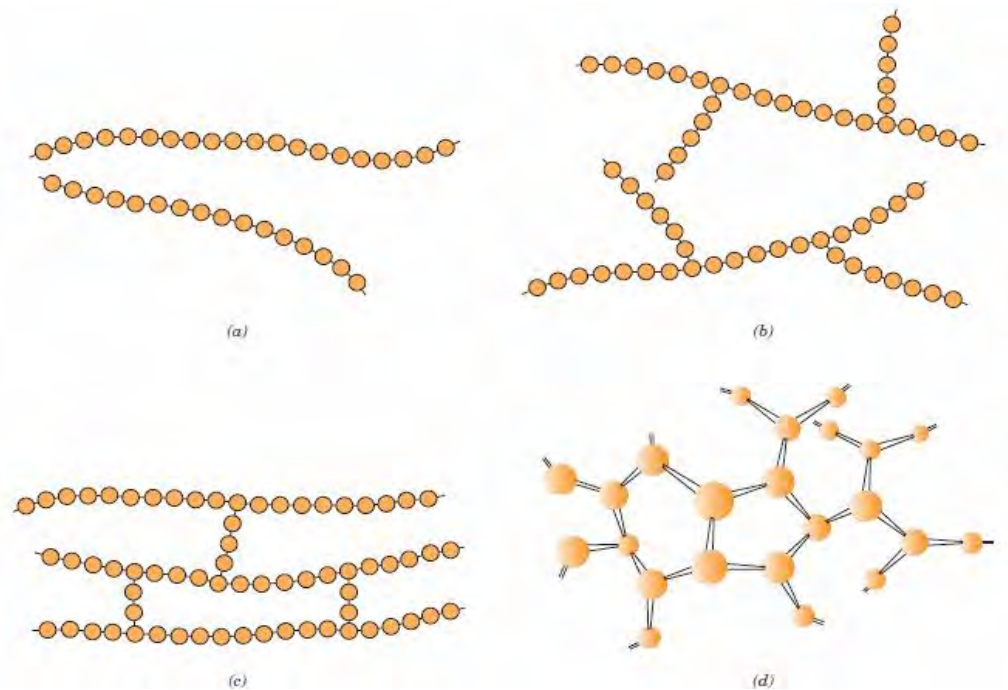


(b)

Figure 2. For polyethylene, (a) a schematic representation of repeat unit and chain structures, and (b) a perspective of the molecule, indicating the zigzag backbone structure.

Molecular Structure:

The physical characteristics of a polymer depend not only on its molecular weight and shape but also on differences in the structure of the molecular chains. Modern polymer synthesis techniques permit considerable control over various structural possibilities. This section discusses several molecular structures including linear, branched, cross linked, and network, in addition to various isomeric configurations.



Circles designate individual repeat units.

Figure 3. Schematic representations of: (a) linear, (b) branched, (c) cross linked, and (d) network (three-dimensional) molecular structures.

Linear Polymers

They are those in which the repeat units are joined together end to end in single chains. These long chains are flexible and may be thought of as a mass of spaghetti, as represented schematically in Figure 3.a, where each circle represents a repeat unit. For linear polymers, there may be extensive van der Waals and hydrogen bonding between the chains. Some of the common polymers that form with linear structures are polyethylene, poly(vinyl chloride), polystyrene, poly(methacrylate), nylon, and the fluorocarbons.

Branched Polymers

Polymers may be synthesized in which side-branch chains are connected to the main ones, as indicated schematically in Figure 3.b, these are fittingly called **branched polymers**. The branches, considered to be part of the main-chain molecule, may result from side reactions that occur during the synthesis of the polymer. The chain packing efficiency is reduced with the formation of side branches, which results in a lowering of the polymer density. Those

polymers that form linear structures may also be branched. For example, high density polyethylene (HDPE) is primarily a linear polymer, while low density polyethylene (LDPE) contains short chain branches.

Cross linked Polymers

In **cross linked polymers**, adjacent linear chains are joined one to another at various positions by covalent bonds, as represented in Figure 3.c. The process of cross linking is achieved either during synthesis or by a nonreversible chemical reaction.

Often, this cross linking is accomplished by additive atoms or molecules that are covalently bonded to the chains.

Network Polymers

Multifunctional monomers forming three or more active covalent bonds, make three-dimensional networks (Figure 3.d) and are termed **network polymers**. Actually, a polymer that is highly cross linked may also be classified as a network polymer. These materials have distinctive mechanical and thermal properties; the epoxies, polyurethanes, and phenol-formaldehyde belong to this group.

Polymers are not usually of only one distinctive structural type. For example, a predominantly linear polymer might have limited branching and cross linking.

General properties of polymeric materials

The properties of polymeric materials can vary widely, but they all have certain properties in common:

1. *Electrical insulation*

All polymeric materials exhibit good electrical insulation properties. However, their usefulness in this field is limited by their low heat resistance and their softness. Thus they are useless as formers on which to wind electric radiator elements, and as insulators for use out of doors where their relatively soft surface would soon be roughened by the weather. Dirt collecting on this roughened surface would then provide a conductive path, causing a short circuit.

2. *Strength/weight ratio*

Polymeric materials vary in strength considerably. Some of the stronger, such as nylon, compare favorably with the weaker metals. All polymeric materials are much lighter than any of the metals used for engineering purposes. Therefore, properly chosen and proportioned, their strength/weight ratio compares favorably with many light alloys and they are steadily taking over engineering duties which, until recently, were considered the prerogative of metal.

3. Corrosion resistance

All polymeric materials are inert to most inorganic chemicals and can be used in environments which are hostile even to the most corrosion-resistant metals. The synthetic rubbers, which are a product of polymer chemistry, are superior to natural (polyisoprene) since they are not attacked by oils and greases.

Mechanical Behavior of Polymers / Stress–Strain Behavior:

The mechanical properties of polymers are specified with many of the same parameters that are used for metals that is, modulus of elasticity, and yield and tensile strengths. For many polymeric materials, the simple stress–strain test is employed for the characterization of some of these mechanical parameters. The mechanical characteristics of polymers, for the most part, are highly sensitive to the rate of deformation (strain rate), the temperature, and the chemical nature of the environment (the presence of water, oxygen, organic solvents, etc.). Some modifications of the testing techniques and specimen configurations used for metals are necessary with polymers, especially for the highly elastic materials, such as rubbers.

Three typically different types of stress–strain behavior are found for polymeric materials, as represented in Figure 4. Curve *A* illustrates the stress–strain character for a brittle polymer, inasmuch as it fractures while deforming elastically. The behavior for a plastic material, curve *B*, is similar to that for many metallic materials; the initial deformation is elastic, which is followed by yielding and a region of plastic deformation. Finally, the deformation displayed by curve *C* is totally elastic; this rubber-like elasticity (large recoverable strains produced at low stress levels) is displayed by a class of polymers termed the **elastomers**.

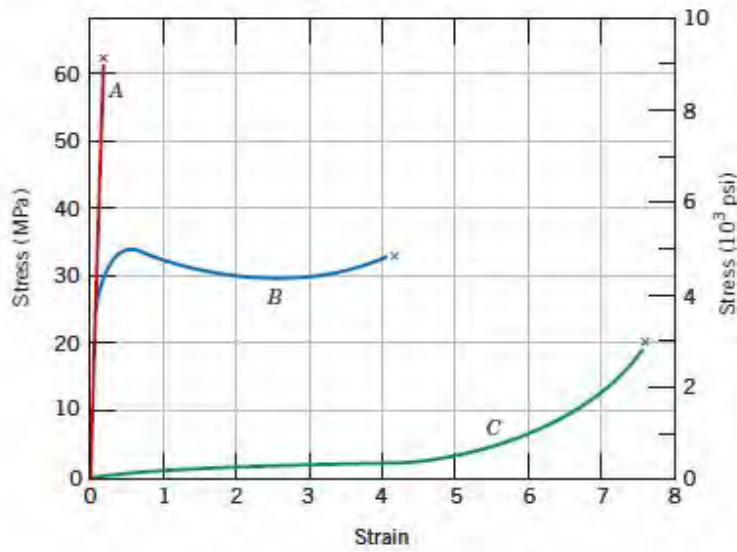


Figure 4. The stress–strain behavior for brittle (curve *A*), plastic (curve *B*), and highly elastic (elastomeric) (curve *C*) polymers.

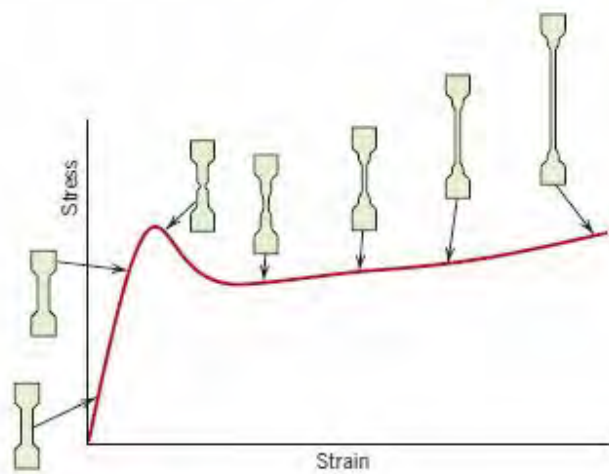


Figure 5. Schematic tensile stress–strain curve for a semicrystalline polymer. Specimen contours at several stages of deformation are included.

Fracture of Polymers:

The fracture strengths of polymeric materials are low relative to those of metals and ceramics. As a general rule, the mode of fracture in thermosetting polymers (heavily cross linked networks) is brittle. In simple terms, during the fracture process, cracks form at regions where there is a localized stress concentration (i.e., scratches, notches, and sharp flaws). As with metals, the stress is amplified at the tips of these cracks leading to crack propagation and fracture. Covalent bonds in the network or cross linked structure are severed during fracture.

For thermoplastic polymers, both ductile and brittle modes are possible, and many of these materials are capable of experiencing a ductile-to-brittle transition. Factors that favor brittle fracture are a reduction in temperature, an increase in strain rate, the presence of a sharp notch, increased specimen thickness, and any modification of the polymer structure that raises the glass transition temperature. Glassy thermoplastics are brittle below their glass transition temperatures.

One phenomenon that frequently precedes fracture in some thermoplastic polymers is **crazing**. Associated with crazes are regions of very localized plastic deformation, which lead to the formation of small and interconnected microvoids (Figure 6.a).

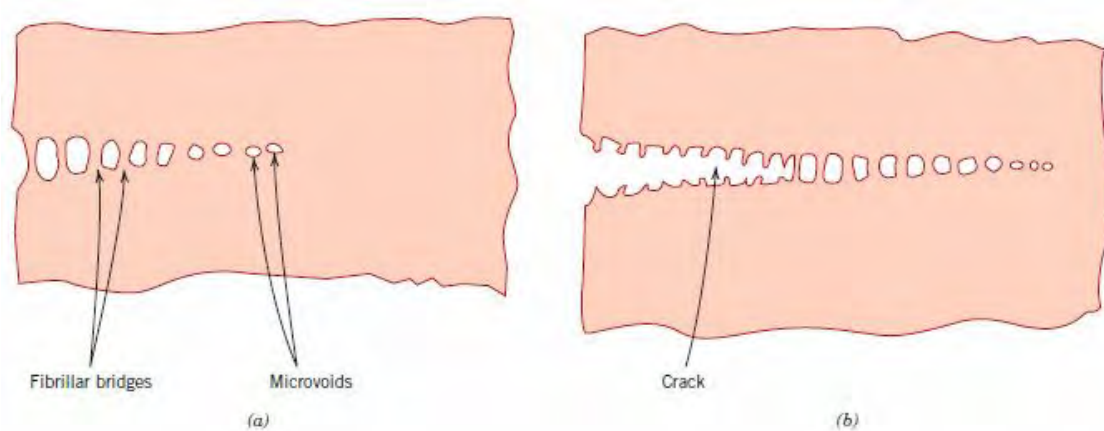


Figure 6. Schematic drawings of (a) a craze showing microvoids and fibrillar bridges, and (b) a craze followed by a crack.

Polymer Types :

There are many different polymeric materials that are familiar to us and find a wide variety of applications; in fact, one way of classifying them is according to their end use.

Within this scheme the various polymer types include plastics, elastomers (or rubbers), fibers, coatings, adhesives, foams, and films. Depending on its properties, a particular polymer may be used in two or more of these application categories.

For example, a plastic, if cross linked and utilized above its glass transition temperature, may make a satisfactory elastomer. Or a fiber material may be used as a plastic if it is not drawn into filaments. This portion of the chapter includes a brief discussion of each of these types of polymer.

1. Plastics:

Possibly the largest number of different polymeric materials come under the plastic classification. **Plastics** are materials that have some structural rigidity under load, and are used in general-purpose applications. Polyethylene, polypropylene, poly(vinyl chloride), polystyrene, and the fluorocarbons, epoxies, phenolics, and polyesters may all be classified as plastics. They have a wide variety of combinations of properties.

Some plastics are very rigid and brittle (Figure 15.1, curve *A*). Others are flexible, exhibiting both elastic and plastic deformations when stressed, and sometimes experiencing considerable deformation before fracture (Figure 4, curve *B*).

Polymers falling within this classification may have any degree of crystallinity, and all molecular structures and configurations (linear, branched, isotactic, etc.) are possible. Plastic materials may be either thermoplastic or thermosetting; in fact, this is the manner in which they are usually subclassified. However, to be considered plastics, linear or branched polymers must be used below their glass transition temperatures (if amorphous) or below their melting temperatures (if semicrystalline), or must be cross linked enough to maintain their shape.

Several plastics exhibit especially outstanding properties. For applications in which optical transparency is critical, polystyrene and poly(methyl methacrylate) are especially well suited; however, it is imperative that the material be highly amorphous or, if semicrystalline, have very small crystallites. The fluorocarbons have a low coefficient of friction and are extremely resistant to attack by a host of chemicals, even at relatively high temperatures. They are utilized as coatings on nonstick cookware, in bearings and bushings, and for high-temperature electronic components.

The advantages of plastics:-

The grate increase in the use of plastics is due to

- their many useful properties,
- couples with comparatively low cost,
- their low densities,
- their high resistance to chemical attack,
- their thermal and electrical insulation properties,
- their ease of fabrication in to a wide variety of both simple and complex shapes.

The disadvantages of plastics :-

The main disadvantages of plastics are :

- The low strength and elastic modulus values, in compression with those of metals
- The low softening and thermal degradation temperature
- Their comparatively high thermal expansion coefficients.

2. Fibers:

The **fiber** polymers are capable of being drawn into long filaments having at least a 100:1 length-to-diameter ratio. Most commercial fiber polymers are utilized in the textile industry, being woven or knit into cloth or fabric.

To be useful as a textile material, a fiber polymer must have a host of rather restrictive physical and chemical properties. While in use, fibers may be subjected to a variety of mechanical deformations stretching, twisting, shearing, and abrasion. Consequently, they must have a high tensile strength (over a relatively wide temperature range) and a high modulus of elasticity, as well as abrasion resistance. These properties are governed by the chemistry of the polymer chains and also by the fiber drawing process.

The molecular weight of fiber materials should be relatively high or the molten material will be too weak and will break during the drawing process. Also, because the tensile strength increases with degree of crystallinity, the structure and configuration of the chains should allow the production of a highly crystalline polymer.

That translates into a requirement for linear and unbranched chains that are symmetrical and have regular repeat units. Polar groups in the polymer

also improve the fiber-forming properties by increasing both crystallinity and the intermolecular forces between the chains.

Convenience in washing and maintaining clothing depends primarily on the thermal properties of the fiber polymer, that is, its melting and glass transition temperatures.

Furthermore, fiber polymers must exhibit chemical stability to a rather extensive variety of environments, including acids, bases, bleaches, dry cleaning solvents, and sunlight. In addition, they must be relatively nonflammable and amenable to drying.

Engineering Materials

13

Corrosion & Its Prevention

Introduction :

Corrosion is the slow but continuous eating away of metallic components by chemical or electrochemical attack. That this is costly and destructive will be vouched for by any motorist.

Three factors govern corrosion.

- The metal from which the component is made.
- The protective treatment the component surface receives.
- The environment in which the component is kept.

All metals corrode to a greater or lesser degree; even precious metals like gold and silver tarnish in time, and this is a form of corrosion. Prevention processes are unable to prevent the inevitable failure of the component by corrosion; they only slow down the process to a point where the component will have worn out or been discarded for other reasons before failing due to corrosion. Let's now look at the three ways in which metals corrode.

- **Dry corrosion** This is the direct oxidation of metals which occurs when a freshly cut surface reacts with the oxygen of the atmosphere. Most of the corrosion-resistant metals such as lead, zinc and aluminum form a dry oxide film which protects the metal from further atmospheric attack.
- **Wet corrosion** This occurs in two ways:
 - a) The oxidation of metals in the presence of air and moisture, as in the rusting of ferrous metals.
 - b) The corrosion of metals by reaction with the dilute acids in rain due to the burning of fossil fuels (acid rain) - for example, the formation of the carbonate 'patina' on copper. This is the characteristic green film seen on the copper clad roofs of some public buildings.
- **Galvanic corrosion** This occurs when two dissimilar metals, such as iron and tin or iron and zinc, are in intimate contact. They form a simple

electrical cell in which rain, polluted with dilute atmospheric acids, acts as an electrolyte as generated and circulates within the system. Corrosion occurs with (depending upon its position in the electrochemical series) being eaten away.

Other metals, in addition to iron and steel, corrode when exposed to the atmosphere. The green corrosion-product which covers a copper roof, or the white, powdery film formed on some unprotected aluminum alloys is clear evidence of this.

Fortunately the reactivity of a metal and the rate at which it corrode is not related. For example, although aluminum is chemically more reactive than iron, as soon as it is exposed to the atmosphere it forms an oxide film which seals the surface and prevents further corrosion from taking place. On the other hand, iron is less reactive and forms its oxide film more slowly. Unfortunately, the iron hydroxide film (rust) is porous and the process continues unabated until the metal is destroyed.

Types of corrosion:-

1. Atmospheric corrosion

Any metal exposed to normal atmospheric conditions become covered with an invisible, thin film of moisture. This moisture film is invariably contaminated with dissolved solids and gases which increase the rate of corrosion. The most common example of corrosion due to dissolved oxygen from the atmosphere is the rapid surface formation of 'red rust' on unprotected ferrous metals. This 'red rust' is a hydroxide of iron and should not be confused with the blue-black oxide of iron called 'mill-scale' which is formed by heating iron in dry air.

Once 'rusting' commences the action is self-generating - that is, it will continue even after the initial supply of moisture and air is removed. This is why all traces of rust must be removed or neutralized before painting, otherwise rusting will continue under the paint, causing it to blister and flake off.

2. Galvanic corrosion

It has already been stated that when two dissimilar metals come into intimate association in the presence of an electrolyte that a simple electrical cell is formed resulting in the eating away of one or other of the metals. Metals can be arranged in a special order called the electrochemical series. This series is listed in Table 1 and it should be noted that, in this context, hydrogen gas behaves like a metal.

Table 1. Electrochemical series

<i>Metal</i>	<i>Electrode</i>
Sodium	-2.71 Corroded (anodic)
Magnesium	-2.40
Aluminium	-1.70
Zinc	-0.76
Chromium	-0.56
Iron	-0.44
Cadmium	-0.40
Nickel	-0.23
Tin	-0.14
Lead	-0.12
Hydrogen (reference potential)	0.00
Copper	+0.35
Silver	+0.80
Platinum	+ 1.20
Gold	+ 1.50 Protected (cathodic)

If any two metals come into contact in the presence of a dilute acid, the more negative metal will corrode more rapidly and will be eaten away.

3. Corrosion accelerated by mechanical stresses

We have seen that failure of a component may take place due to corrosion arising from electrolytic action between two different phases in a microstructure, or between two different materials in a fabricated structure. Failure of a component may also occur as a result of the complementary effects of chemical corrosion and mechanical stress. The methods of stress application may vary and this will affect the extent of corrosion which occurs. Forms of corrosion in which stress plays a part can be classified as follows:

3.1 Stress Corrosion. In a cold-worked metal the pile-up of dislocations at crystal boundaries and other points increases the energy in those regions so that they become anodic to the rest of the structure. Consequently, corrosion takes place in these regions of high energy and the locked-up stresses give rise to the formation of cracks which grow progressively with the continuance of corrosion. A similar process may take place in components in which unequal heating or cooling has given rise to the presence of locked-up stresses, as, for example, near to welded joints.

3.2 Corrosion Fatigue. As might be expected, any component which is subjected to alternating stresses and is working in conditions which promote corrosion may fail at a stress well below the normal fatigue limit (3.72). The action of the corrosive medium will tend to be concentrated at any surface flaw and behave as a focal point for the initiation of a fatigue crack. Once a crack has been formed it will spread more rapidly as a result of the corrosive action combined with alternating stress.

3.3 Fretting Corrosion is allied to corrosion fatigue and occurs particularly where closely fitting machine parts are subjected to vibrational stresses. In steel this form of corrosion appears as patches of finely divided ferric oxide (Fe_2O_3).

3.4 Impingement Corrosion refers to the combined effects of mechanical abrasion and chemical corrosion on a metallic surface. Mechanical wear can be caused by the impingement of entrained air bubbles or abrasive particles suspended in the liquid. The impingement of such media may lead to the perforation of any protective film existing on the surface. This film may be an oxide, which is cathodic to the exposed metal beneath. This type of corrosion is encountered in pump mechanism turbine and tuber carrying sea-water.

Factors affecting corrosions:-

1. Structural design

The following factors should be observed during the design stage of a component or assembly to reduce corrosion to a minimum.

- The design should avoid crevices and corners where moisture may become trapped, and adequate ventilation and drainage should be provided.
- The design should allow for easy washing down and cleaning.
- Joints which are not continuously welded should be sealed, for example, by the use of mastic compounds or impregnated tapes.
- Where dissimilar metals have to be joined, high-strength epoxy adhesives should be considered since they insulate the metals from each other and prevent galvanic corrosion.
- Materials which are inherently corrosion resistant should be chosen or, if this is not possible, an anti-corrosive treatment should be specified.

2. Environment

The environment in which the component or assembly is to spend its service life must be carefully studied so that the materials chosen, or the anti-corrosion treatment specified, will provide an adequate service life at a reasonable cost. It would be unnecessary and uneconomical to provide a piece of office equipment which will be used indoors with a protective finish suitable for heavy-duty contractors plant which is going to work on construction sites in all kinds of weather conditions.

3. Applied or internal stresses

Chemical and electrochemical corrosion is intensified when a metal is under stress. This applies equally to externally applied and internal stresses, although more common in the latter case. Internal stresses are usually caused by cold working and, if not removed by stress-relief heat treatment, results in corrosive attack along the crystal boundaries. This weakens the metal considerably more than simple surface corrosion. An example of intercrystalline corrosion is the 'season cracking' of a brass after severe cold working.

Intercrystalline corrosion occurs at the grain boundaries of crystals not only when impurities are present but also when stress concentrations are present. Grain boundaries are regions of high energy levels, even in very pure

metals, so corrosion tends to occur more quickly at the grain boundaries. Severely cold-worked α brasses are prone to 'season cracking'. Here, intercrystalline corrosion follows the grain boundaries until the component is no longer able to sustain the internal stresses due to cold working. The component then cracks. This can be prevented by a low-temperature stress relief annealing process. This low temperature does not cause recrystallisation but is sufficient to remove the locked up stresses by allowing the atoms to move small distances nearer to their equilibrium positions.

4. Composition and structure

The presence of impurities in non-ferrous metals reduces their corrosion resistance. Hence the high level of corrosion resistance exhibited by high-purity copper, aluminum and zinc. The importance of grain structure has also been mentioned above, and a fine-grain structure is generally less susceptible to corrosion than a coarse-grain structure. The inclusion of certain alloying elements such as nickel and chromium can also improve corrosion resistance - for example, the stainless steels and cupro-nickel alloys.

5. Temperature

For all chemical reactions there is a critical temperature below which they will not take place. Since corrosion is the result of chemical or electrochemical reactions, corrosion is retarded or stopped altogether at low temperatures. On the other hand, corrosion is at its worst in the hot, humid atmosphere of the tropical rain forests, and equipment for use in such environments has to be 'tropicalised' if it is to have a reasonable service life. High temperatures alone do not increase the rate of corrosion, and corrosion is virtually nonexistent in arid desert areas of the world. Failure of mechanical devices in desert environments is due generally to the abrasive effect of the all-pervasive sand.

Metals which resist corrosion

It has already been made clear that metals combine with atmospheric oxygen and or atmospheric pollutants to a greater or lesser extent. The following metals, which resist corrosion, react to form impervious, homogeneous coatings on their surfaces which prevent further corrosion from taking place, providing these coatings remain undisturbed.

Such as copper, zinc, aluminum , lead, stainless steel, nickel and chromium.

The protection of corrosion:-

There are two principal methods by which corrosion may be prevented or minimized. First, the metallic surface can be insulated from the corrosive medium by some form of protective coating. Such coatings include various types of paints and varnishes, metallic films having good corrosion-resistance and artificially thickened oxide films. All of these are generally effective in protecting surfaces from atmospheric corrosion, though zinc coatings are used to protect iron from the rusting action of water, whilst tin coatings offer protection against most animal and vegetable juices encountered in the canning industry.

In circumstances where corrosive action is severe, or where mechanical abrasion is likely to damage a surface coating, it may be necessary to use a metal or alloy which has an inherent resistance to corrosion. Such corrosion-resistant alloys are relatively expensive, so that their use is limited generally to chemical- engineering plant, marine-engineering equipment and other special applications.

There are many types of the protection from corrosion, which they are:-

1) The Use of a Metal or Alloy Which Is Inherently Corrosion-resistant

The corrosion-resistance of a pure metal or a homogeneous solid solution is generally superior to that of an alloy in which two or more phases are present in the microstructure. As mentioned above, the existence of two phases leads to electrolytic action when the surface of the alloy comes into contact with an electrolyte.

Most of the alloys which are used because of their high corrosion-resistance exhibit solid-solution structures. Aluminum-

magnesium alloys containing up to 7-0% magnesium fulfil these conditions and are particularly resistant to marine atmospheres. Stain less steel of the "18-8" type is completely austenitic in structure when correctly heat-treated, but faulty heat-treatment may lead to the precipitation of carbides and, hence, to corrosion. Although such corrosion is partly due to the impoverishment of the austenitic matrix in chromium (since it is mainly chromium carbide which is precipitated), this corrosion is accelerated by electrolytic action between the carbide particles and the matrix. "Weld-decay" in steels of this type occurs for similar reasons.

2) Protection by Metallic Coatings

Protection afforded by metallic coatings can be either "direct" or "sacrificial". Direct protection depends on an unbroken film of metal covering the article, and if the film becomes broken, corrosion may be accelerated by electrolytic action between the film and the metal beneath. In the case of sacrificial protection, however, the metallic film becomes the anode in the event of a break in the film, and thus dissolves in preference to the surface beneath. It follows that, when protection is limited to the direct type, as in the case of tin coatings on steel, the quality of the coating is most important, since acceleration, and not inhibition, of corrosion would follow a break in the film. In both cases, of course, protection of the direct type is the fundamental aim of the metal-coating process, and it is only in the possibility of the coating becoming broken that the effects of electrolytic action must be considered.

A number of methods are available for the production of metallic coatings. The most widely used are either electro-plating or dipping the articles to be coated into a bath of the molten metal. In some cases a successful coating can be produced by heating the articles to be coated in the finely powdered metal, whilst specialised use is made of the process known as "cladding".

2.1 Cladding.

This process is applicable chiefly to the manufacture of "clad" sheet. The basis metal is sandwiched between pieces of the coating metal, and the sandwich is rolled to the required thickness. "Alclad", which is duralumin coated with pure aluminum, is possibly the best known of these products, whilst "Ni clad" (nickel-coated steel) is also manufactured.

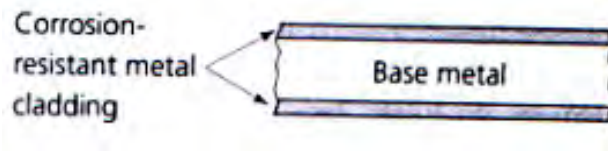


Figure 1. Sectional through clad metal composite.

2.2 Hot-dip Metal Coating

Tin and zinc are the metals most often used to produce metallic coatings in this manner, though increasing use is being made of aluminum.

- (a) **Hot-dip Tinning.**
- (b) **Hot-dip Galvanising**
- (c) **Hot-dip Coating with Aluminum.**

2.3 Coating by means of a spray of molten metal

Metal spraying consists in projecting "atomised" particles of molten metal from a special pistol by a stream of compressed air on to a suitably prepared surface. Surface preparation usually involves blasting the surface with an abrasive; steel grit having replaced sharp silica sand for this purpose on account of the silicosis hazards involved when the latter is used. The metal most commonly used for spraying is zinc, though coatings of aluminium, tin, lead, solder, cadmium, silver, copper and stainless steel can be deposited in this way.

In yet another process invented by **Dr. Schoop**, the originator of metal-spraying processes, electricity is used in place of gas for heating in those pistols which utilise zinc wire. In this pistol an arc is struck between two zinc wires so that their ends melt continuously as the wires are fed forward. The metal particles are carried forward by a stream of compressed air.

Metal spraying has wide application in view of its portability and flexibility; thus, large structures, such as storage tanks, pylons and bridges, can be sprayed on site. Notable recent examples include the Forth Road Bridge and the Volta River Bridge (Ghana), both of which were zinc coated using modern developments of the Schoop process.

2.4 Electro-plating

The formation of metal coatings by electro-deposition is well known, and a wide variety of metals can be thus used, including copper, nickel, chromium, cadmium, gold and silver. Tin and zinc can also be electro-deposited, and a coating thus formed has advantages over one produced by hot-dipping in respect of flexibility, uniformity and control of thickness of film.

In the actual process of electro-plating the article to be plated is made the cathode in an electrolytic cell. Sometimes the metal to be deposited is contained, as a soluble salt, in the electrolyte, in which case the anode is a non-reactive conductor, such as stainless steel, lead or carbon. In most cases, however, the anode consists of a plate of the pure metal which is being deposited, whilst the electrolyte will contain a salt or salts of the same metal. Then, the anode gradually dissolves and maintains the concentration of the metal in the electrolyte as it is deposited on to the articles forming the cathode.

The conditions under which deposition takes place are very important, so that the cell voltage, the current density (measured in amperes per square meter of cathode surface), the ratio of anode area to cathode area and the time of deposition, as well as the composition and temperature of the electrolyte, must all be strictly controlled if a uniform adherent and non-ferrous film is to be obtained.

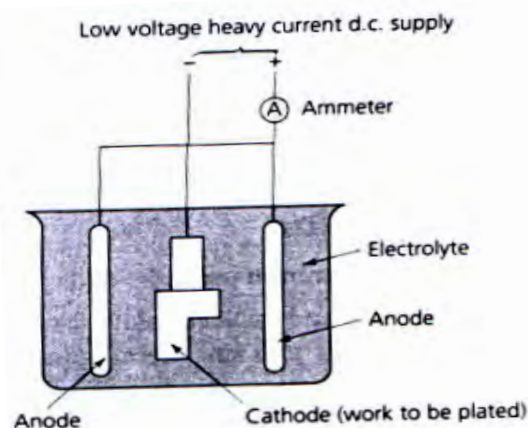


Figure 2. The electro plating.

3) Protection by oxide coating

In some instances the film of oxide which forms on the surface of a metal is very dense and closely adherent. It will then protect the metal surface beneath from oxidation. Stainless steels owe their resistance to corrosion to the presence of a high proportion of chromium, which is one of these elements that form oxide films impervious to oxygen. The "blueing" of ordinary carbon steel by heating it in air produces an oxide film of such a nature that it affords partial protection from corrosion.

Anodizing. Reference has already been made to the protection afforded aluminum by the natural film of oxide which forms on its surface. Anodic oxidation, or anodising, is an electrolytic process for thickening this oxide film. This process may be applied for several reasons, such as to provide a "key" for painting, to provide an insulating coating for an electrical conductor or to provide a surface which may be dyed, as well as to increase the resistance of aluminum to corrosion.

Before being anodised the surface of the article must be chemically clean. Preliminary treatment involves sand-blasting, scratch brushing or barrel polishing, according to the nature of the component. This is followed by degreasing in either the liquid or vapour of electrolytic cleaning.

In the actual anodising operation which follows, the aluminum article to be treated is made the anode in an electrolyte containing either chromic, sulphuric or oxalic acid; the cathode being a plate of lead or stainless steel. When an electric current is passed, oxygen is formed at the anode and immediately combines with the aluminum surface of the article. The layer of oxide thus formed grows outwards from the surface of the aluminum. The normal thickness of a satisfactory anodic film produced commercially varies between 0.007 and 0.015 mm., and a film having a thickness within these limits would be formed by anodising a component in a 15% sulphuric acid solution at 20° C for about thirty minutes, using a current density of about 100 A/m² at a cell voltage of 15. A longer period of treatment produces a thicker, but soft and spongy, film which would be unsatisfactory in service. The thickness of the natural film produced on an aluminum surface by exposure to air at normal temperatures is of the order of 0.000 013 mm.

Anodising

Aluminum and aluminum alloy components are cleaned and degreased. After which they are etched, wire-brushed or polished depending upon the surface texture required. The work is then made the anode of an electrolytic cell (see electroplating, where the work is the cathode) and a direct current is passed through the cell. The electrolyte is a dilute acid and varies with the finish and protection required. Colours may be integral or applied subsequently by dyeing. The purpose of the treatment is to increase the thickness of the natural, protective oxide film and improve the corrosion resistance of the metal.

4) Protection by other nonmetallic coatings

Coatings of this type usually offer only a limited protection against corrosion and are, more often than not, used only as a base for painting.

4.1 Phosphating

A number of commercial processes fall under this heading, but in all of them a coating of phosphate is produced on the surface of steel or zinc-base alloys by treating them in or with a solution of acid phosphates. In order that the metal shall be made rust-proof a finishing treatment with varnish, paint, oil or lacquer is required.

4.2 Chromating

Chromate coatings are produced on magnesium-base alloys, and on zinc and its alloys, by immersing the articles in a bath containing potassium bichromate along with various other additions. The colour of the films varies with the bath and alloy, from yellow to grey and black.

5) Cathodic protection

This method of protection against corrosion can be used for buried or submerged pipe-lines and other structures. The pipe-line is made to act as a cathode by burying near it pieces of a metal which is much more electropositive than the iron of the pipe-line. These pieces of metal will therefore be anodic towards the iron of the pipe-line and will corrode sacrificially.

Alternatively, a current from D.C. mains can be passed through the soil or water on to the metallic surface concerned so as to keep it at a slightly negative potential with respect to its surroundings. When electric power is available this will be the cheaper method, since electricity can be obtained more cheaply from the mains than from any electro-chemical source. To protect the whole surface of a pipe-line by this means, however, would be expensive, but if the pipe has already been coated with paint or some other non-metallic substance, so that it is only necessary to protect any defective areas, the power cost is small, since very small currents only are necessary. In some parts of America the current is generated by dynamos driven by windmills.

Engineering Materials

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Ceramics

Introduction:

Ceramics are compounds between metallic and nonmetallic elements; they are most frequently oxides, nitrides, and carbides. For example, some of the common ceramic materials include aluminum oxide (or alumina, Al_2O_3), silicon dioxide (or *silica*, SiO_2), silicon carbide (SiC), silicon nitride (Si_3N_4), and, in addition, what some refer to as the *traditional ceramics* those composed of clay minerals (i.e., porcelain), as well as cement, and glass.

Up until the past 60 or so years, the most important materials in this class were termed the “traditional ceramics,” those for which the primary raw material is clay; products considered to be traditional ceramics are china, porcelain, bricks, tiles, and, in addition, glasses and high-temperature ceramics. Of late, significant progress has been made in understanding the fundamental character of these materials and of the phenomena that occur in them that are responsible for their unique properties.

Consequently, a new generation of these materials has evolved, and the term “ceramic” has taken on a much broader meaning. To one degree or another, these new materials have a rather dramatic effect on our lives; electronic, computer, communication, aerospace, and a host of other industries rely on their use.

With regard to mechanical behavior, ceramic materials are relatively stiff and strong. Stiffnesses and strengths are comparable to those of the metals. In addition, ceramics are typically very hard. On the other hand, they are extremely brittle (lack ductility), and are highly susceptible to fracture.

These materials are typically insulative to the passage of heat and electricity, and are more resistant to high temperatures and harsh environments than metals and polymers. Several common ceramic objects are shown in the photograph of Figure 1.



Figure 1. Common objects that are made of ceramic materials: scissors, a china tea cup, a building brick, a floor tile, and a glass vase.

Impurity atoms can form solid solutions in ceramic materials much as they do in metals. Solid solutions of both substitutional and interstitial types are possible.

Ceramic Phase Diagrams:

Phase diagrams have been experimentally determined for a large number of ceramic systems. For binary or two-component phase diagrams, it is frequently the case that the two components are compounds that share a common element, often oxygen. These diagrams may have configurations similar to metal–metal systems, and they are interpreted in the same way.

As an example, one of the relatively simple ceramic phase diagrams is that found for the aluminum oxide–chromium oxide system, Figure 2. This diagram has the same form as the isomorphous copper–nickel phase diagram, consisting of single liquid and single solid phase regions separated by a two-phase solid–liquid region having the shape of a blade. The solid solution is a substitutional one in which Al^{3+} substitutes for Cr^{3+} and vice versa. It exists for all compositions below the melting point of inasmuch as both aluminum and chromium ions have the same charge as well as similar radii (0.053 and 0.062 nm, respectively). Furthermore, both Al_2O_3 and Cr_2O_3 have the same crystal structure.

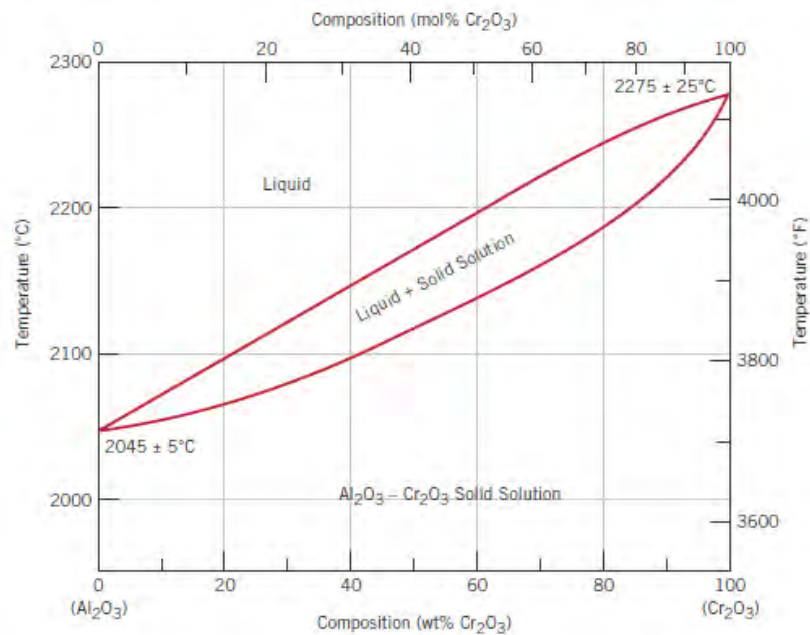


Figure 2. The aluminum oxide – chromium oxide phase diagram.

Mechanical Properties :

Ceramic materials are somewhat limited in applicability by their mechanical properties, which in many respects are inferior to those of metals.

❖ Brittle Fracture of Ceramics:

The brittle fracture process consists of the formation and propagation of cracks through the cross section of material in a direction perpendicular to the applied load. Crack growth in crystalline ceramics may be either transgranular (i.e., through the grains) or intergranular (i.e., along grain boundaries); for transgranular fracture, cracks propagate along specific crystallographic (or cleavage) planes, planes of high atomic density.

❖ Stress–Strain Behavior:

At room temperature, virtually all ceramics are brittle. Microcracks, the presence of which is very difficult to control, result in amplification of applied tensile stresses and account for relatively low fracture strengths (flexural strengths). This amplification does not occur with compressive loads, and, consequently, ceramics are stronger in compression.

The stress at fracture using this flexure test is known as the **flexural strength**, *modulus of rupture*, *fracture strength*, or the *bend strength*, an important mechanical parameter for brittle ceramics.

❖ Hardness

One beneficial mechanical property of ceramics is their hardness, which is often utilized when an abrasive or grinding action is required; in fact, the hardest known materials are ceramics.

❖ Creep

Often ceramic materials experience creep deformation as a result of exposure to stresses (usually compressive) at elevated temperatures. In general, the time deformation creep behavior of ceramics is similar to that of metals; however, creep occurs at higher temperatures in ceramics. High-temperature compressive creep tests are conducted on ceramic materials to ascertain creep deformation as a function of temperature and stress level.

Types and Applications of Ceramics:

Most ceramic materials fall into an application-classification scheme that includes the following groups: glasses, structural clay products, white wares, refractories, abrasives, cements, and the newly developed advanced ceramics as shown in Figure 3.

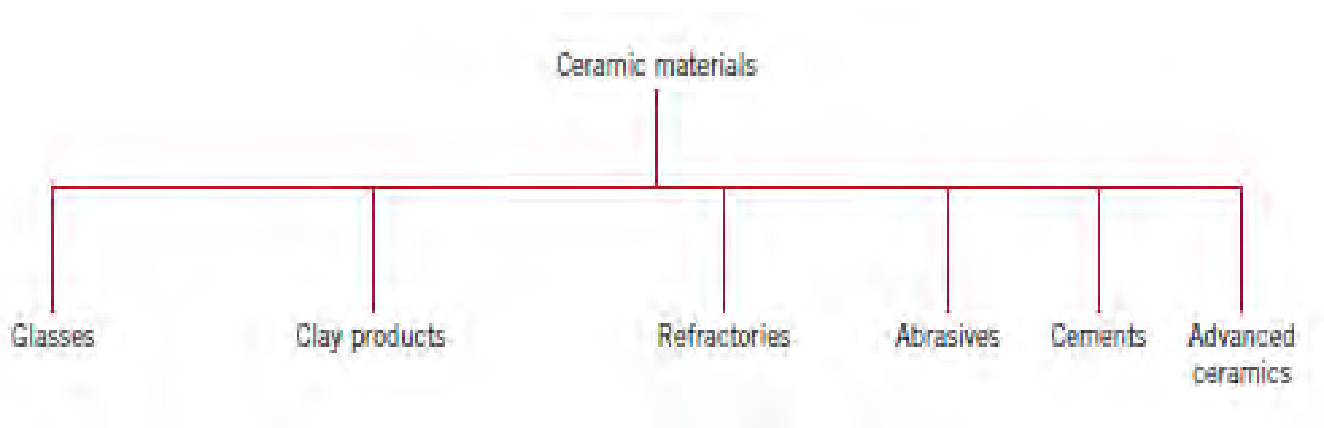


Figure 3. Classification of ceramic materials on the basis of application.

1) Glasses

The glasses are a familiar group of ceramics; containers, lenses, and fiberglass represent typical applications. Most inorganic glasses can be made to transform from a noncrystalline state to one that is crystalline by the proper high-temperature heat treatment. This process is called **crystallization**, and the product is a fine-grained polycrystalline material which is often called a **glass-ceramic**. The formation of these small glass-ceramic grains is, in a sense, a phase transformation, which involves nucleation and growth stages.

Glass-ceramic materials have been designed to have the following characteristics:

- ✓ relatively high mechanical strengths;
- ✓ low coefficients of thermal expansion (to avoid thermal shock);
- ✓ relatively high temperature capabilities; good dielectric properties (for electronic packaging applications); and
- ✓ good biological compatibility.

The most common uses for these materials are as ovenware, tableware, oven windows, and range tops—primarily because of their strength and excellent resistance to thermal shock. They also serve as electrical insulators and as substrates for printed circuit boards, and are used for architectural cladding, and for heat exchangers and regenerators.

2) Clay Products

One of the most widely used ceramic raw materials is clay. This inexpensive ingredient, found naturally in great abundance, often is used as mined without any upgrading of quality. Another reason for its popularity lies in the ease with which clay products may be formed; when mixed in the proper proportions, clay and water form a plastic mass that is very amenable to shaping. The formed piece is dried to remove some of the moisture, after which it is fired at an elevated temperature to improve its mechanical strength.

3) Refractories

Another important class of ceramics that are utilized in large tonnages is the **refractory ceramics**. The salient properties of these materials include the capacity to withstand high temperatures without melting or decomposing, and the capacity to remain unreactive and inert when exposed to severe environments. In addition, the ability to provide thermal insulation is often an important consideration.

Refractory materials are marketed in a variety of forms, but bricks are the most common. Typical applications include furnace linings for metal refining, glass manufacturing, metallurgical heat treatment, and power generation.

Of course, the performance of a refractory ceramic, to a large degree, depends on its composition. On this basis, there are several classifications namely, fireclay, silica, basic, and special refractories.

4) Abrasives

Abrasive ceramics are used to wear, grind, or cut away other material, which necessarily is softer. Therefore, the prime requisite for this group of materials is hardness or wear resistance; in addition, a high degree of toughness is essential to ensure that the abrasive particles do not easily fracture. Furthermore, high temperatures may be produced from abrasive frictional forces, so some refractoriness is also desirable.

Diamonds, both natural and synthetic, are utilized as abrasives; however, they are relatively expensive. The more common ceramic abrasives include silicon carbide, tungsten carbide (WC), aluminum oxide (or corundum), and silica sand.

5) Cements

Several familiar ceramic materials are classified as inorganic **cements**: cement, plaster of paris, and lime, which, as a group, are produced in extremely large quantities.

The characteristic feature of these materials is that when mixed with water, they form a paste that subsequently sets and hardens. This trait is especially useful in that solid and rigid structures having just about any shape may be expeditiously formed. Also, some of these materials act as a bonding phase that chemically binds particulate aggregates into a single cohesive structure. Under these circumstances, the role of the cement is similar to that of the glassy bonding phase that forms when clay products and some refractory bricks are fired. One important difference, however, is that the cementitious bond develops at room temperature.

6) Advanced Ceramics

Many of our modern technologies utilize and will continue to utilize advanced ceramics because of their unique mechanical, chemical, electrical, magnetic, and optical properties and property combinations.

Engineering Materials

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Deformation in Metals

Introduction:

After studying the mechanical properties of metals, we learned that deformation can occur either by elastic movement or by plastic flow.

Elastic flow in metals:

In elastic deformation a limited distortion of the crystal lattice is produced, but the atoms do not move permanently from their ordered positions, and as soon as the stress is removed the distortion disappeared. When metal is stressed beyond the elastic limit plastic deformation takes place and there must, clearly, be some movement of the atoms into new positions, since considerable permanent distortion can be produced. Our present task, then, is to consider ways in which this extensive rearrangement of atoms within the lattice structure can take place to give rise to this permanent deformation.

Plastic flow in metals:

As mentioned previously, many materials possess an elastic limit and when stressed they strain in an elastic manner up to a certain point. Beyond THIS POINT THE STRAIN developed is no longer directly proportional to the applied stress, and also, the strain developed is no longer fully recoverable. If the stress is removed elastic strain is recovered but the material will be left in a state of permanent, or plastic, strain. The mechanism of plastic deformation is not the same for all classes of materials and it is necessary to consider the various materials groups separately. Metals, in general, are characterized by possessing high elastic modulus values, and also the ability to be strained in a plastic manner. Some metals will begin to deform plastically at very low values of stress and will yield to a very considerable extent before fracture occurs. Other metals and alloys show little plastic yielding before fracture. These latter materials are termed brittle. Plastic deformation in metals may take place by the process of slip, or by twinning.

1) Slip

It is the deformation done by one layer or plan of atoms gliding over another.

An early theory evolved to explain plastic deformation in metals was the 'block slip' theory. In this it was postulated that when the yield stress of the metal was exceeded plastic deformation took place by the movement of large blocks of atoms sliding relative to one another across certain planes — slip planes — within the crystal as shown in Figure 1.

The 'block slip' theory accounted for many of the observed phenomena but possessed a number of drawbacks, one of which being that the theoretical yield strength of a metal, calculated on the basis of this theory, was about a thousand times greater than the experimentally observed strengths of pure metals. Present-day theories of plastic flow in metals are based on the existence of small imperfections, or defects, within crystals. These are structural defects, termed dislocations, and plastic deformation is due to the movement of dislocations across the slip planes of a crystal under the action of an applied stress. The calculated stress required to bring about the movement of dislocations is of the same order of magnitude as observed yield stresses in metals. In recent years it has been possible to produce small single crystals that are virtually defect free. These small perfect crystals, termed *whiskers*, possess properties close to the very high theoretical strengths predicted for perfectly crystalline metals.

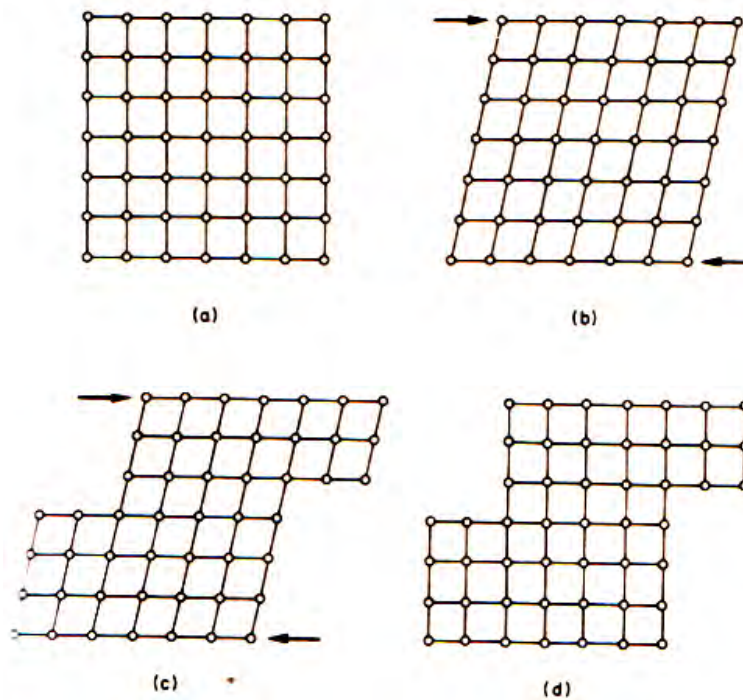


Figure 1. Plastic deformation according to the 'block slip' theory, (a) Original unstressed condition, (b) Elastic strain only. Specimen will revert to (a) when the stress is removed, (c) Elastic and plastic deformation. When stress is removed the specimen will appear as in (d). (d) Unstressed. No elastic strain but permanent plastic strain remains.

If the slip planes were aligned either normal to, or parallel to, the stress axis, failure occurred in a brittle manner with negligible plastic deformation as in Figure 2. If, however, the slip planes were inclined at some angle, θ , other than 0° or 90° , plastic yielding took place before failure.

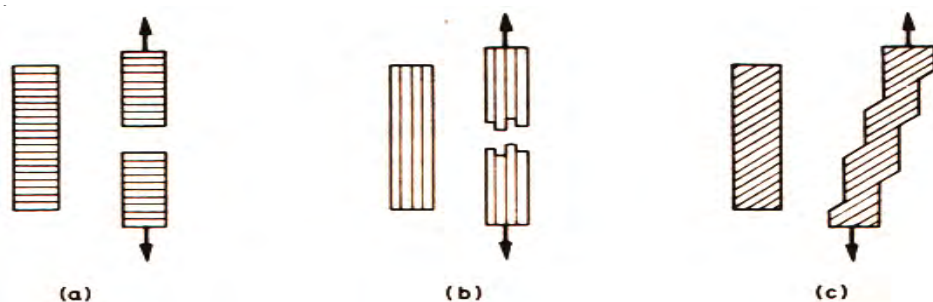


Figure 2. Effect of stress on single crystals of hexagonal metal. (a) Slip planes normal to the applied stress; brittle fracture; no slip. (b) Slip planes in line with the applied stress; brittle fracture; no slip. (c) Slip planes inclined to the applied stress; slip and plastic deformation caused by shear force acting on slip planes.

2) Twinning

In addition to deformation by slip, some metals, notably zinc, tin and iron, deform by a process known as "**twinning**". The mechanism of this process is illustrated in Figure 3. In deformation by slip all atoms in one block move the same distance, but in deformation by twinning, atoms in each successive plane within a block will move different distances, with the effect of altering the direction of the lattice so that each half of the crystal becomes a mirror image of the other half. It is thought that twinning also proceeds by the movement of dislocations. The twins thus formed are called "mechanical twins" to distinguish them from the "annealing twins" which become apparent in copper alloys during an annealing operation which follows cold work. The mechanical twins formed in iron by a sudden shock are called "Neumann bands".

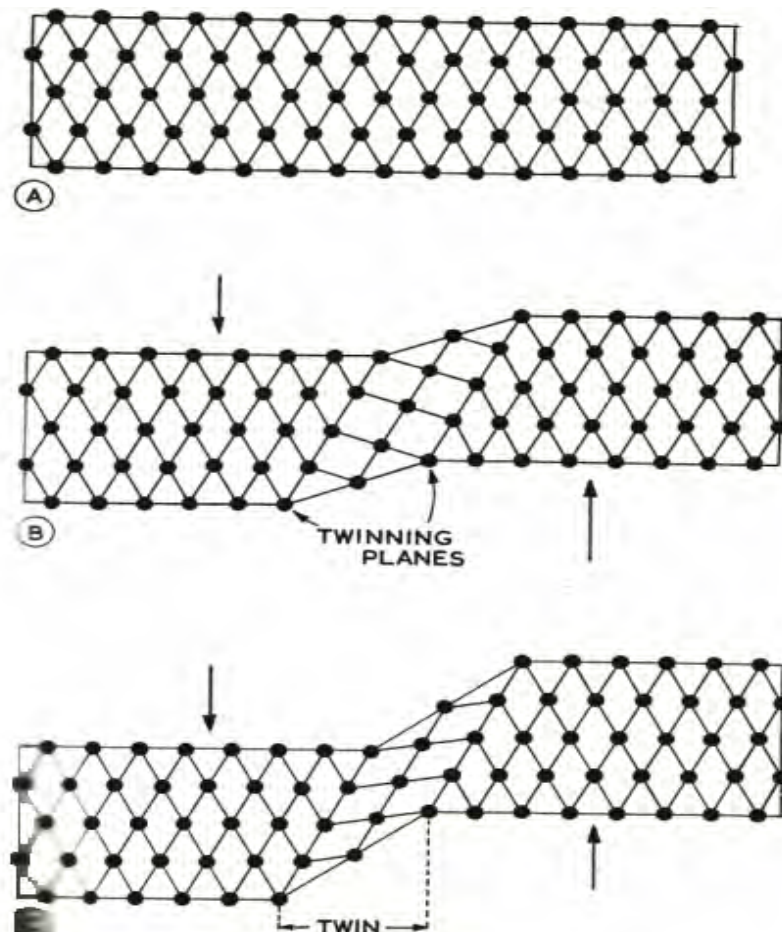


Figure 3. The formation of "Mechanical Twins".

Plastic deformation and strain hardening:

When a metal is stressed beyond its elastic limit dislocations within the metal begin to move and plastic deformation occurs. The movement of one dislocation through a lattice will give one increment of plastic deformation, namely a displacement of the order of one atomic spacing. The movement of extremely large numbers of dislocations would be necessary to give a visible amount of plastic slip and the number of dislocations that would need to be present to account for the large amount of plastic deformation that takes place in commercial metal-working processes such as rolling or forging would be so great as to mean that there would be virtually no regular sections of lattice at all. In fact, the number of dislocations present in a fully annealed metal is comparatively small and additional dislocations are generated during plastic deformation.

Energy of Mechanical Deformation:

As deformation proceeds, the metal becomes harder and stronger, and, whether by slip or by twinning, a stage is reached when no more deformation can be produced. An increase in the applied force will then lead only to fracture. In this state, when tensile strength and hardness have reached a maximum and elongation a minimum, the material is said to be work-hardened. Thus we can summarise the effects of mechanical deformation briefly as follows - if sufficient stress is applied to a metal, slip (or twinning) will take place in individual crystals. As deformation proceeds, the capacity for slip decreases that the force necessary to produce it must increase. A point is reached, coinciding with the maximum resistance to slip (the maximum strength and hardness), where no more deformation is possible and fracture will take place. The material must then be annealed if further cold work is to be carried out on it.

During a cold-working process approximately 90 % of the mechanical energy employed is turned into heat, whilst the remaining 10 % is stored inside the material as mechanical potential energy. The bulk of this stored energy (9 % of that originally employed) is that associated with the number of dislocations present. These have energy because they distort the lattice and cause atoms to occupy positions of higher-than-minimum energy. The remaining stored energy (1 % of the energy

originally employed) exists as locked-up residual stresses arising from elastic strains internally balanced.

The increased-energy state of a cold-worked metal makes it chemically more active and consequently less resistant to corrosion. This is particularly true of micro-stresses acting at grain boundaries and leading to increased intercrystalline corrosion by causing the grain boundaries to corrode more quickly than the rest of the material. This stored potential energy is also the main driving force of recrystallisation.

Annealing and Recrystallisation:

A cold-worked metal is in a state of considerable mechanical stress, resulting from elastic strains internally balanced. These elastic strains are largely due to unhomogeneous deformation having taken place during cold-working. If the metal is heated to a sufficiently high temperature these strains will be removed; at the same time the tensile strength and hardness of the metal will fall to approximately their original value and the capacity for cold-work return. This form of heat treatment is known as annealing, and is made use of when the metal is required for use in a soft but tough state or, alternatively, when it is to undergo further cold deformation. Annealing takes place in three stages as follows:

Stage I - The Relief of Stress

Stage II - Recrystallisation.

Stage III - Grain Growth.

Engineering Materials

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The industrial shaping of metals

Introduction:

Materials have to be processed into a great variety of shapes in order to make component parts of every type. The shapes required vary enormously, both in size and complexity, ranging from micro-electronic components to large castings and forgings of , perhaps, several hundred tones mass (1 tones = 1000 kg = 1 Mg). The engineer must have some awareness of the range of manufacturing processes available, and of the advantages and limitations of the various processes. The properties of the material in the finished component are also influenced to a considerable extent by the type of shaping process employed, and by the conditions existing during processing.

Metals and alloys may be shaped into something approaching the final required form by one of the following operations:

- (a) casting into either a sand or a metal mould;
- (b) casting as an ingot followed by a hot-working process;
- (c) casting as an ingot followed by a cold-working process;
- (d) sintering from a powdered metal.

There are, it is true, other processes, such as electro-deposition and the condensation of metal vapours, but these operations are usually confined to the surface treatment of metallic components rather than to their actual shaping. Electro-deposition is sometimes used to build up parts which have become badly worn.

FORMING OPERATIONS

Forming operations are those in which the shape of a metal piece is changed by plastic deformation; for example, forging, rolling, extrusion, and drawing are common forming techniques. Of course, the deformation must be induced by an external force or stress, the magnitude of which must exceed the yield strength of the material. Most metallic materials are especially amenable to these procedures, being at least moderately ductile and capable of some permanent deformation without cracking or fracturing.

When deformation is achieved at a temperature above that at which recrystallization occurs, the process is termed **hot working** ; otherwise, it is cold working. With most of the forming techniques, both hot- and cold-working procedures are possible. For hot-working operations, large deformations are possible, which may be successively repeated because the metal remains soft and ductile. Also, deformation energy requirements are less than for cold working.

However, most metals experience some surface oxidation, which results in material loss and a poor final surface finish. **Cold working** produces an increase in strength with the attendant decrease in ductility, since the metal strain hardens; advantages over hot working include a higher quality surface finish, better mechanical properties and a greater variety of them, and closer dimensional control of the finished piece. On occasion, the total deformation is accomplished in a series of steps in which the piece is successively cold worked a small amount and then process annealed ; however, this is an expensive and inconvenient procedure.

An example of the forming operations are illustrated schematically in Figure 1.

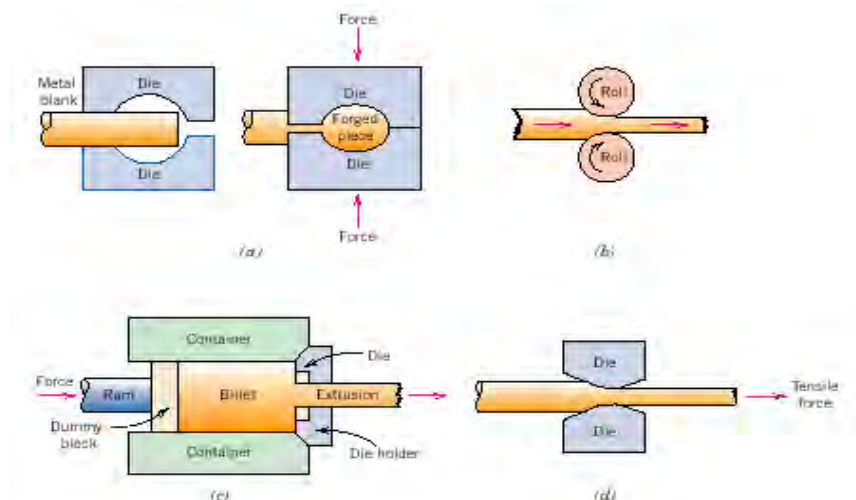


Figure 1. Metal deformation during (a) forging, (b) rolling, (c) extrusion, and (d) drawing.

1. Casting

Casting is a fabrication process whereby a totally molten metal is poured into a mold cavity having the desired shape; upon solidification, the metal assumes the shape of the mold but experiences some shrinkage. Casting techniques are employed when (1) the finished shape is so large or complicated that any other method would be impractical, (2) a particular alloy is so low in ductility that forming by either hot or cold working would be difficult, and (3) in comparison to other fabrication processes, casting is the most economical. Furthermore, the final step in the refining of even ductile metals may involve a casting process. A number of different casting techniques are commonly employed, including sand, die, investment, lost foam, and continuous casting. Only a cursory treatment of each of these is offered.

Sand Casting

With sand casting, probably the most common method, ordinary sand is used as the mold material. A two-piece mold is formed by packing sand around a pattern that has the shape of the intended casting. Furthermore, a *gating system* is usually incorporated into the mold to expedite the flow of molten metal into the cavity and to minimize internal casting defects. Sand-cast parts include automotive cylinder blocks, fire hydrants, and large pipe fittings.

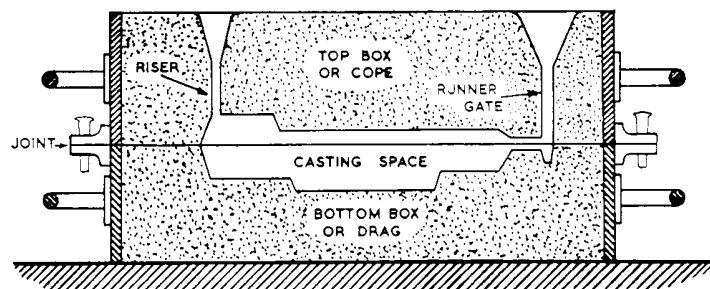


Figure 2. Mould for a Sand-casting.

Die Casting

In die casting, the liquid metal is forced into a mold under pressure and at a relatively high velocity, and allowed to solidify with the pressure maintained. A two piece permanent steel mold or die is employed; when clamped together, the two pieces form the desired shape. When complete solidification has been achieved, the die pieces are opened and the cast piece is ejected. Rapid casting rates are possible, making this an inexpensive method; furthermore, a single

set of dies may be used for thousands of castings. However, this technique lends itself only to relatively small pieces and to alloys of zinc, aluminum, and magnesium, which have low melting temperatures.

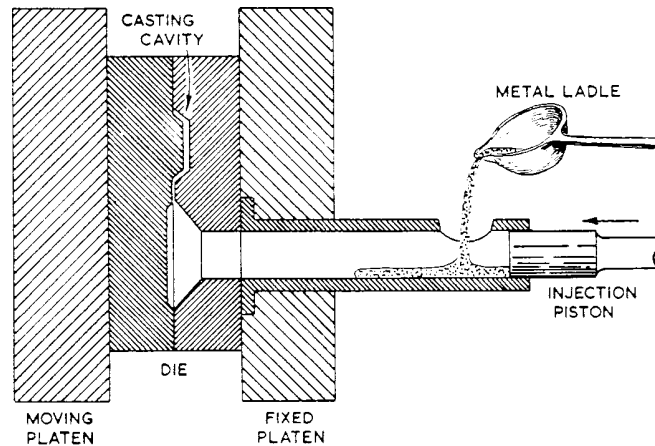


Figure 3. A Pressure Die-casting Machine.

2. Hot Working

Any increase in the temperature of a metal leads to an increase in atomic spacings so that the bond strength will decrease slightly. Moreover, a dislocation does not produce as much distortion and can move more easily through the crystal. Consequently the yield strength falls as the temperature rises.

However, hot-working operations invariably take place above the recrystallisation temperature of a metal or alloy. The importance of this will be at once apparent. Deformation and recrystallisation will be taking place simultaneously, so that a considerable speeding-up of the process is possible, with no tedious inter-stage anneals as are necessary in cold-deformation processes.

Moreover, with most alloys, malleability and plasticity are considerably increased at high temperatures, so that far less power is needed to produce deformation. With some alloys it is essential to use a hot-working process, since they are hard or brittle when cold, owing to the presence of a hard micro-constituent which is absorbed at the hot-working temperature.

There are many types of hot working processes which are: **Hot –rolling, Forging, Prop-forging, Heading, Hot-pressing and Extrusion.** The main hot-working processes are dealt with are below:

- Hot – rolling

Hot-rolling is universally applied to the "breaking-down" of large steel ingots to sections, strip, sheet and rod of various sizes. In fact, the only conditions under which cold-work is applied to steel are when the section is too small to retain its heat, or when a superior finish is required in the product.

A steel-rolling shop consists of a powerful "two-high" reversing mill, to break down the white-hot ingots, followed by trains of rolls which will be either plain or grooved according to the type of product being manufactured. Hot-rolling is similarly applied to most of the non-ferrous alloys in the initial breaking-down stages, but the finishing operations are more likely to involve cold-work.

- Forging

The simplest and most ancient working process known to metallurgical industry is essentially that which was employed by Tubal Cain, and which is still employed by a skilled blacksmith. Although power-driven hammers are now used, skill is still necessary on the part of the smith, since he works with comparatively simple shaping tools known as "swages".

Wrought iron is always associated with the blacksmith, but many other ferrous and non-ferrous alloys can be shaped by both hand and mechanical forging processes. During forging, the coarse "as-cast" structure is broken down and replaced by one which is of relatively fine grain. At the same time impurities are redistributed in a more or less fibrous form. Therefore it is more satisfactory, all other things being equal, to forge a component than to cast it to shape.

- Extrusion

The extrusion process is now used for shaping a variety of ferrous and non-ferrous metals and alloys. Its most important feature is that we are able to force the metal through a die, and, in a single process from the cast billet, to obtain quite complicated sections of tolerably accurate dimensions. The metal billet is heated to the required extrusion temperature and placed in the container of the extrusion press. The ram is then driven hydraulically with sufficient pressure to force the metal through a hard alloy-steel die.

the solid metal section issues from the die in a manner similar to the flow of toothpaste from its tube.

Using this process, a wide variety of sections can be produced, including round rod, hexagonal brass rod (for parting off as nuts), brass curtain rail, small-diameter rod (for drawing still further to wire), tubes 'tress-bearing sections in aluminum alloys (mainly for aircraft construction).

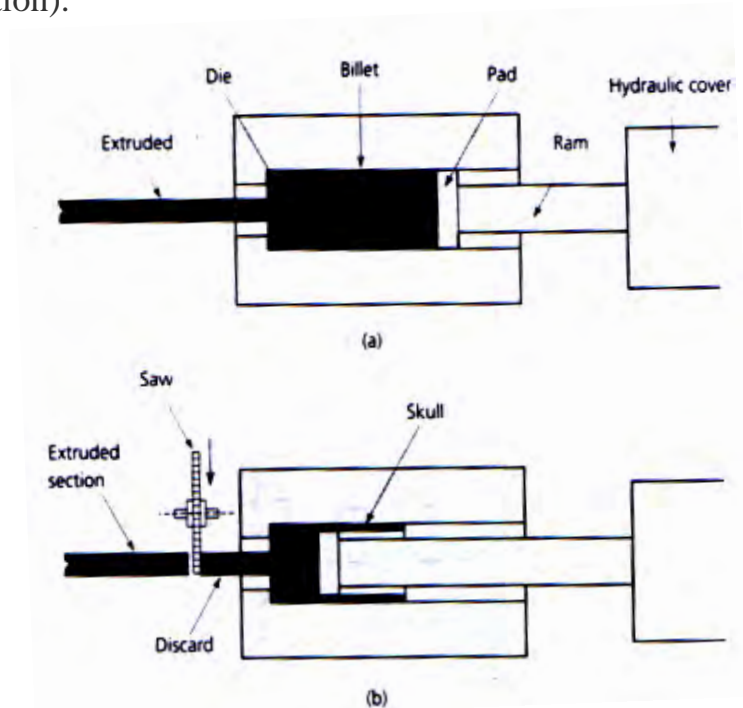


Figure 4. Extrusion (a) commencement of extrusion stroke; (b) completion of extrusion stroke.

3. Cold Working

Cold-working from the ingot to the finished product, with, of course, the necessary intermediate annealing stages, is applied only in the case of a few alloys. These include both alloys which are very malleable in the cold and, on the other hand, those which become brittle when heated.

Cold-working is more often applied in the finishing stages of production. Then its functions are:

- (a) to enable accurate dimensions to be attained in the finished product
- (b) to obtain a clean, smooth finish;

(c) by adjusting the amount of cold-work in the final operation after annealing, to obtain the required degree of hardness, or "temper", in alloys which cannot be hardened by heat-treatment.

Raising the temperature of an alloy generally increases its malleability, but reduces its ductility because of the attendant reduction in yield strength. Thus in hot-working processes we are always *pushing* the alloy into shape, whilst in cold-working operations we frequently make use of the high ductility of some alloys when cold, *by pulling* them into their required shapes. Therefore, processes involving the putting or "drawing" of metal through a die are always cold-working operations.

There are many cold-working processes, but the principal ones used in metallurgical industries are below:

Cold-rolling, Drawing of solid and Hollow sections, Cold-pressing and Deep-drawing, Coining and Spinning.

- Cold-rolling.

Cold-rolling is applied during the finishing stages of production of both strip and section and also in the production of very thin materials such as foil. In most other cases cold-rolling mills are similar in design to those used for hot-rolling. The production of mirror-finished metal foil is carried out in rolls enclosed in an "air-conditioned" cubicle, and the rolls themselves are polished frequently with clean cotton wool. Only by working in perfectly clean surroundings, with highly polished rolls, can really high grade foil be obtained.

In addition to quality of finish, the objects of cold-rolling are accuracy of dimensions and the adjustment of the correct temper in the material.

- Coining

Coining, or embossing, is really a cold-forging process and, as its name implies, it is used for the production of coinage, medallions and the like. It has also been used on an experimental scale for producing engineering components to exact dimensions. A malleable alloy is essential for this type of process if excessive wear on the dies is to be avoided.

4. Sintering from a Powder

This method of producing metallic structures has become increasingly important in recent years, and is particularly useful when there is a big difference in the melting points of the metals to be alloyed, or when a metal has an extremely high melting point. As an example, products containing a high proportion of tungsten are usually formed by sintering, since this metal is difficult and expensive to melt on a commercial scale.

The metal to be sintered is obtained as a fine powder, either by grinding; by volatilisation and condensation; or by reduction of its powdered oxide. Any necessary mixing is carried out, and the mixed powdered metals are then placed in a hardened steel die and compressed. The pressures used vary with the metals to be sintered, but are usually between 70 and 700 N mm². The brittle compressed mass is then heated in a small electric furnace to a temperature which will cause sintering to take place and produce a mechanically satisfactory product. Sintering will often occur below the melting point of either metal, though frequently it is above the melting point of one of them.

Engineering Materials

17

Composite materials

Introduction:

As was mentioned that alloys of metals with non-metals could only occur if all the component materials were miscible, that is, soluble in each other in the molten state. Composite materials can be made up from materials that are not soluble in each other. Composite materials are not alloys.

In its simplest form a composite material consists of two dissimilar materials in which one material forms a matrix to bond together the other (reinforcement) material. The matrix and reinforcement are chosen so that their mechanical properties complement each other, whilst their deficiencies are neutralised. For example, in GRP moulding, the polyester resin is the matrix that binds together the glass fiber reinforcement.

Material property combinations and ranges have been extended by the development of composite materials. Generally speaking, a composite is considered to be any multiphase material that exhibits a significant proportion of the properties of both constituent phases such that a better combination of properties is realized. According to this **principle of combined action**, better property combinations are fashioned by the judicious combination of two or more distinct materials. Property trade-offs are also made for many composites.

In designing composite materials, scientists and engineers have ingeniously combined various metals, ceramics, and polymers to produce a new generation of extraordinary materials. Most composites have been created to improve combinations of mechanical characteristics such as stiffness, toughness, and ambient and high-temperature strength.

In a 'composite', the *reinforcement* material, in the form of rods, strands, fibers or particles, is bonded together with the other *matrix* materials. For example, the fibers may have some of the highest moduli and greatest strengths available in tension, but little resistance to bending and compressive

forces. On the other hand, the matrix can be chosen to have high resistance to bending and compressive forces. Used together these two different types of material produce a composite with high tensile and compressive strengths and a high resistance to bending.

Structural Composites

A **structural composite** is normally composed of both homogeneous and composite materials, the properties of which depend not only on the properties of the constituent materials but also on the geometrical design of the various structural elements. Laminar composites and sandwich panels are two of the most common structural composites; only a relatively superficial examination is offered here for them.

LAMINAR COMPOSITES

A **laminar composite** is composed of two-dimensional sheets or panels that have a preferred high-strength direction such as is found in wood and continuous and aligned fiber-reinforced plastics. The layers are stacked and subsequently cemented together such that the orientation of the high-strength direction varies with each successive layer in Figure 1. For example, adjacent wood sheets in plywood are aligned with the grain direction at right angles to each other. Laminations may also be constructed using fabric material such as cotton, paper, or woven glass fibers embedded in a plastic matrix. Thus a laminar composite has relatively high strength in a number of directions in the two-dimensional plane; however, the strength in any given direction is, of course, lower than it would be if all the fibers were oriented in that direction.

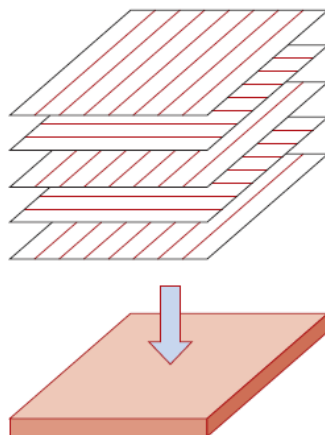


Figure 1. The stacking of successive oriented, fiber-reinforced layers for a laminar composite.

Brittle materials such as concrete and ceramics are strong in compression but weak in tension since they are susceptible to crack propagation, as shown in Figure 2 (a). The use of composite materials overcomes this problem by preventing the crack from 'running'. Two ways in which a crack can be prevented from running are:

- The use of lamination, as shown in Figure 2(b).
- The use of reinforcing fibres which hold the brittle matrix in compression, so an external tensile load cannot open up any surface cracks and discontinuities (Figure 2(c)).

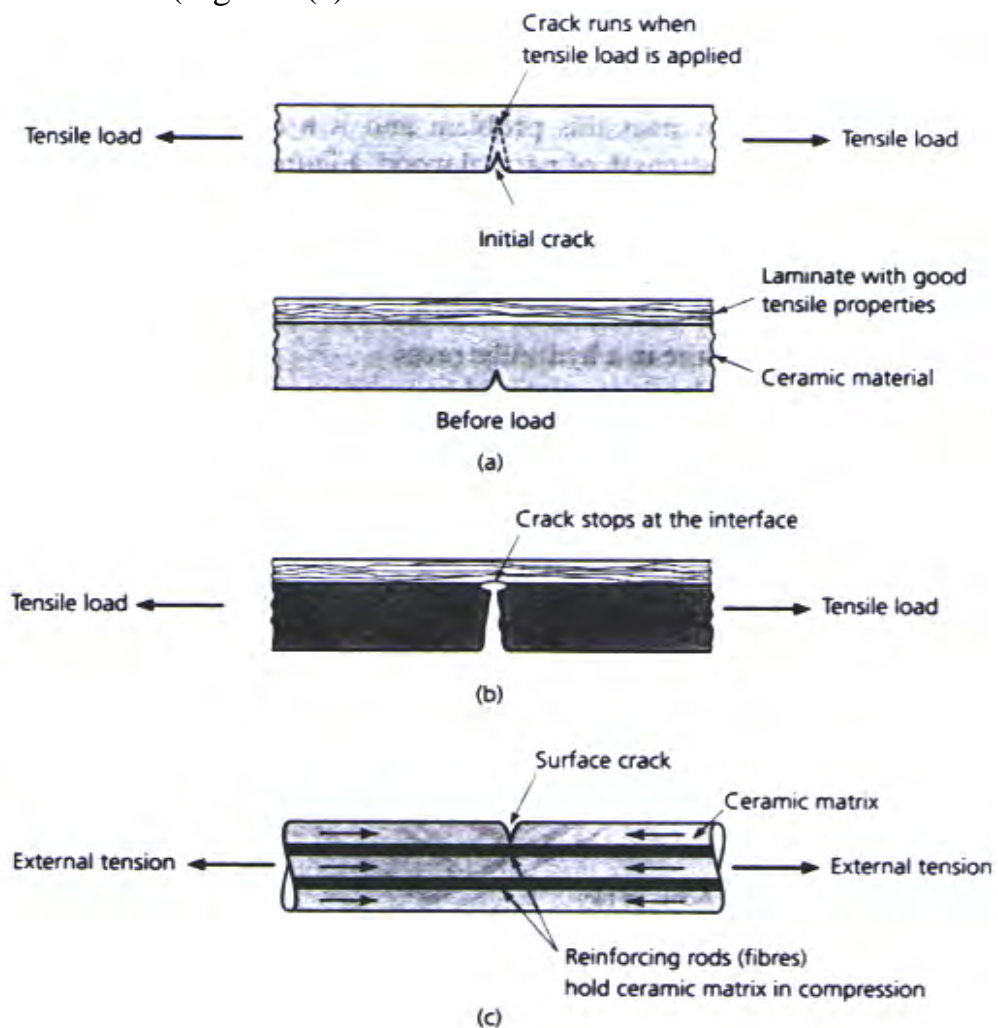


Figure 2. Principles of reinforced composite materials: (a) crack propagation in a non-reinforced ceramic material, (b) behavior of a laminated composite when in tension; (c) fibre reinforcement

PLYWOOD

Wood like all materials reinforced *by* parallel fibres, has highly directional strength characteristics. Figure 3(a) shows a plank being bent in a *plane perpendicular* to the lay of the grain. Loading the plank in this way exploits its greatest strength characteristics. Figure 3(b) shows what would happen if a piece of wood is loaded so that bending occurs *parallel* to the lay of the grain. The wood breaks easily since the lignin bond is relatively weak compared with the natural cellulose reinforcement fibres.

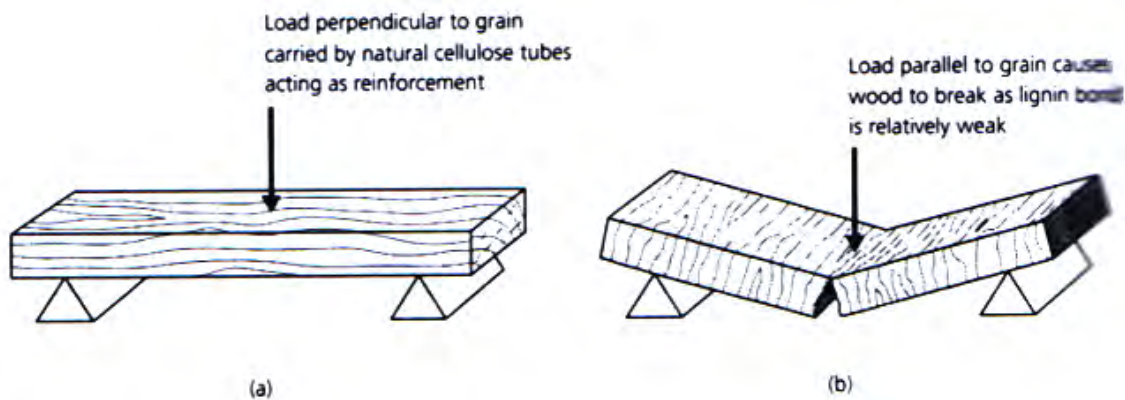


Figure 3. Effect of the direction of grain on the strength of wood.

Plywood overcomes this problem and is a man-made composite which exploits the directivity of the strength of natural wood. Figure 4, shows how plywood is built up from veneers (thin sheets of wood) bonded together by a high-strength and water-resistant synthetic resin adhesive. When laying up the veneers, care is taken to ensure that the grain of each successive layer is perpendicular (at right angles) to the preceding layer. When the correct number of veneers have been laid up, the adhesive component of the composite is cured under pressure in a hydraulic press.

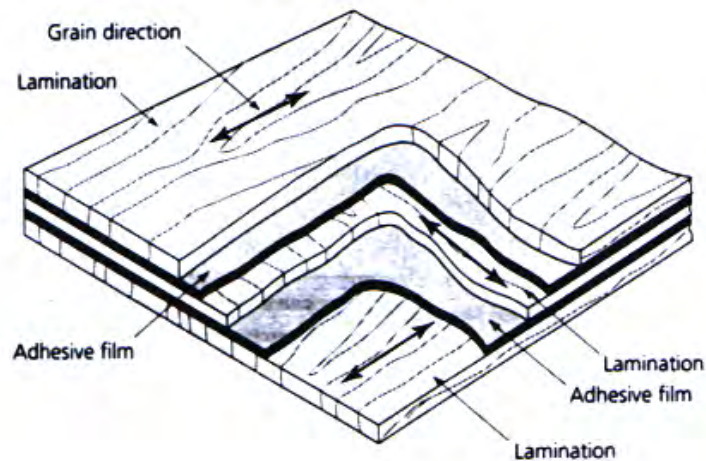


Figure 4. Structure of plywood.

SANDWICH PANELS

Sandwich panels, considered to be a class of structural composites, are designed to be light-weight beams or panels having relatively high stiffnesses and strengths. A sandwich panel consists of two outer sheets, or faces, that are separated by and adhesively bonded to a thicker core as shown in Figure 5. The outer sheets are made of a relatively stiff and strong material, typically aluminum alloys, fiber-reinforced plastics, titanium, steel, or plywood; they impart high stiffness and strength to the structure, and must be thick enough to withstand tensile and compressive stresses that result from loading. The core material is lightweight, and normally has a low modulus of elasticity. Core materials typically fall within three categories: rigid polymeric foams (i.e., phenolics, epoxy, polyurethanes), wood (i.e., balsa wood), and honeycombs.

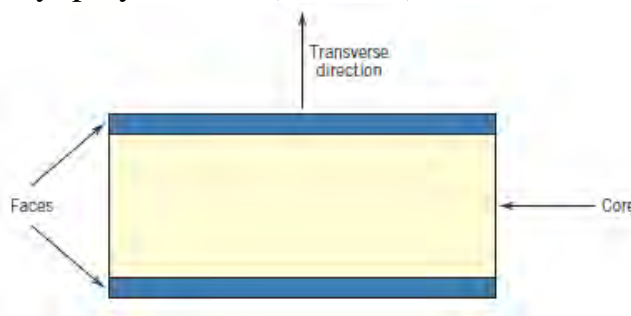


Figure 5. Schematic diagram showing the cross section of a sandwich panel.

Structurally, the core serves several functions. First of all, it provides continuous support for the faces. In addition, it must have sufficient shear strength to withstand transverse shear stresses, and also be thick enough to provide high shear stiffness (to resist buckling of the panel). (It should be noted that tensile and compressive stresses on the core are much lower than on the faces.)

Another popular core consists of a “honeycomb” structure—thin foils that have been formed into interlocking hexagonal cells, with axes oriented perpendicular to the face planes; Figure 6 shows a cutaway view of a honeycomb core sandwich panel. The honeycomb material is normally either an aluminum alloy or aramid polymer. Strength and stiffness of honeycomb structures depend on cell size, cell wall thickness, and the material from which the honeycomb is made. Sandwich panels are used in a wide variety of applications including roofs, floors, and walls of buildings; and, in aerospace and aircraft (i.e., for wings, fuselage, and tailplane skins).

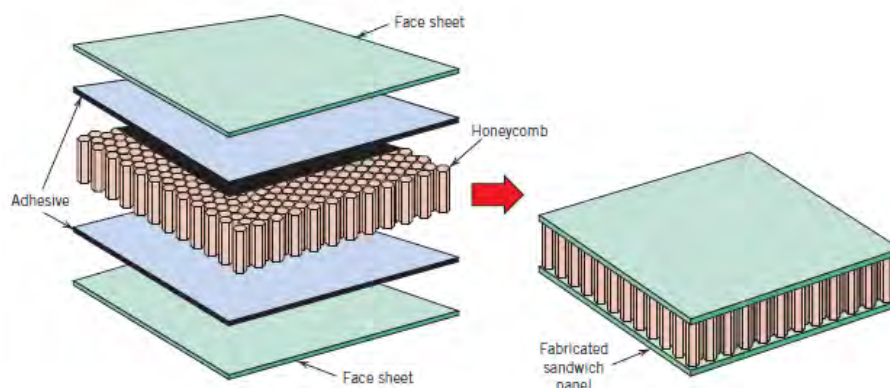


Figure 6. Schematic diagram showing the construction of a honeycomb core sandwich panel.

Fiber reinforcement

Technologically, the most important composites are those in which the dispersed phase is in the form of a fiber. Design goals of **fiber-reinforced composites** often include high strength and/or stiffness on a weight basis. These characteristics are expressed in terms of **specific strength** and **specific modulus** parameters, which correspond, respectively, to the ratios of tensile strength to specific gravity and modulus of elasticity to specific gravity.

This method of reinforcement can range from the glass fibres used in GRP plastic mouldings to the thick steel rods used to reinforce concrete.

1. Reinforced concrete

Concrete itself is a particle-reinforced material. It consists of a mortar made from a hydraulic cement and sand, reinforced with an *aggregate* of chipped stones as shown in figure 7. The stones are crushed so that they have a rough texture and sharp corners that will *key* into and bond with the mortar matrix. This basic concrete has a very high compressive strength but is very weak in tension. To improve its performance overall, metal reinforcing rods are added, as shown in Figure 8.

As well as the amount of reinforcement, the positioning of the reinforcement is also important. Since concrete is strong in compression but weak in tension, it would seem sensible to insert the reinforcement near the tension side of the beam, as shown in figure 8. The tension side is the side of the beam that is on the outside of the 'bend' when the beam 'gives' under the effect of an externally applied load.

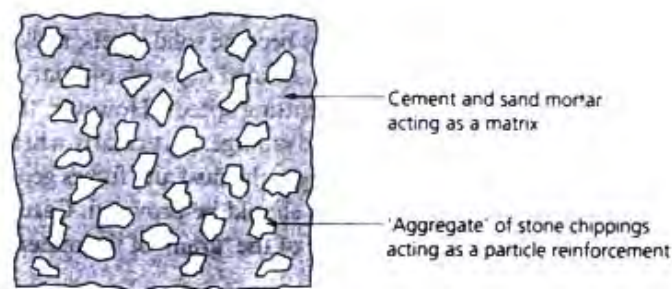


Figure 7. Structure of concrete.

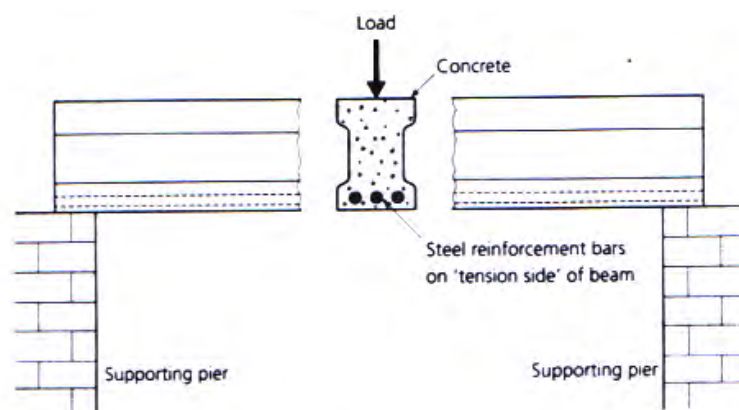


Figure 8. Simple reinforced concrete beam.

2. Glass-reinforced plastic (GRP)

This important composite material is produced when a plastic material, usually a polyester resin is reinforced with glass fibre in strand or mat form. The resin is used to provide shape, colour and finish, whilst the glass fibres, which are laid in all directions, impart mechanical strength.

When a GRP moulding is correctly 'laid up', the thick, viscous resin completely surrounds and adheres to the glass fibres of the 'chopped strand mat' or the woven fibre glass cloth. The resin sets to give a hard, rigid structure. To shorten the setting time a catalyst (accelerator) is often added to the resin immediately before moulding. To improve the appearance of the 'rough side' of the moulding (the side not in contact with the polished surface of the mould), a surfacing tissue is added made up from finer strands of mat. As shown in Figure 9, Glass-reinforced plastic is widely used for products that require high strength to weight ratios such as boat hulls, car bodies, gliders, etc. It has the advantages of being resistant to most environments and it can be used to form more complex shapes than is possible in wood or sheet metal.

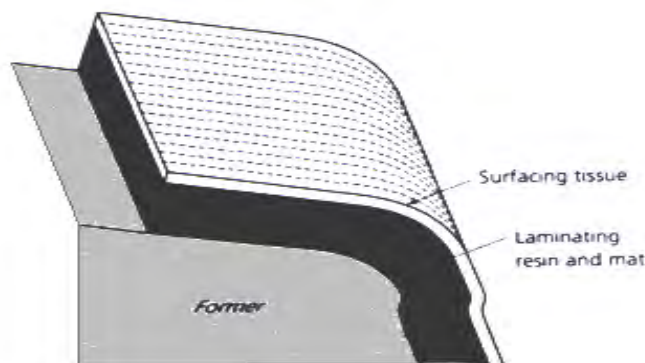


Figure 9. Composition of a GRP lay up.

3. Carbon fibres

These have a higher elastic modulus and lower density than glass fibres, and can be used to reinforce composite materials having a higher strength to weight ratio. Carbon fibers are used as a reinforcement in polymeric materials for a wide range of lightweight, high-strength applications. For example, carbon fibres are used in the manufactures of gas turbine fan blades, racing car body panels, high-performance tennis racket frames and high-performance golf club shafts.

Engineering Materials

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Welding

Introduction:

Welding is an operation of joining metals and alloys. Thus differences between the weld metal and the pieces being joined are structural rather than compositional.

There are many types of joining materials and the alloys which they are :

- 1) Soft soldering
- 2) Brazing
- 3) Welding

There are two types of welding :

1. Fusion welding processes
2. Solid – phase welding processes

1. Fusion welding

In fusion welding any additional material added to the joint has a similar composition and strength to the metals being joined. . Figure 1 shows the principle of fusion welding, where not only the filler metal but also the edges of the components being joined are melted. The molten metals fuse together and, when solid, form a homogeneous joint whose strength is equal to the metals being joined.

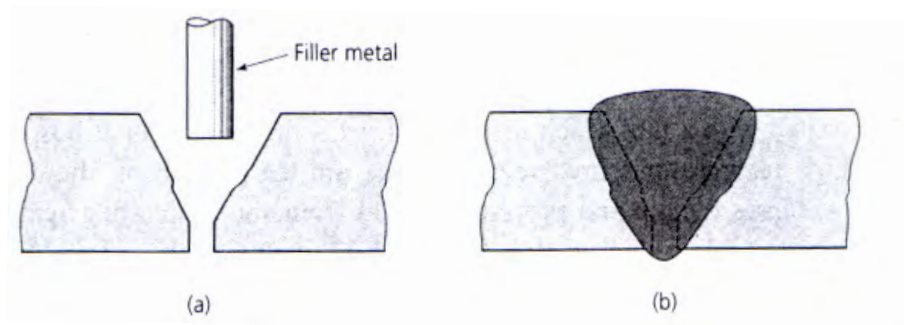


Figure 1. Fusion welding: (a) before - a single 'V' butt requires extra metal: (b) after - the edges of the 'V' are melted and fused together with the molten filler metal.

The fusion welding have some specifications which in this operation the material that is welded is molten a partially moltution, no using for pressure in this operation, the space between the welded materials are filled with a filler.

There are several way to fusion weld such as : oxyacetylene, metallic arc, atomic hydro, laser welding, we will study the most important ways:

a) Oxyacetylene welding

In this process the heat source is a mixture of oxygen and acetylene burning to produce a flame whose temperature can reach 3250 °C. and this is above the melting point of most metals. Figure 2 shows a typical set of welding equipment. The welding gases form a highly flammable and even explosive mixture, so this equipment must only be used by a suitably qualified person or a trainee under the direct instruction of such a person.

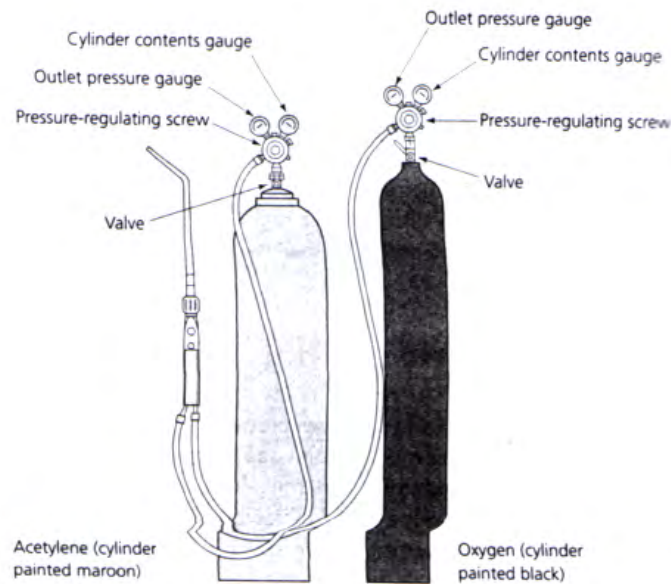


Figure 2 Oxyacetylene welding equipment

b) Metallic arc welding

This is a fusion-welding process where the heat energy required to melt the edges of the components being joined and also the filler rod is supplied by an *electric arc*. The arc is the name given to the prolonged spark struck between two electrodes. In this process the filler rod forms one electrode and the work forms the other electrode. The filler rod/electrode is coated with a flux which melts and shields the joint from atmospheric oxygen at the very high temperatures involved. (Average arc temperature is about 6000 °C.) The flux also stabilises the arc and prevents the rod from short circuiting against the sides of the when welding thick metal. Figure 3 compares the principles of gas and metallic welding.

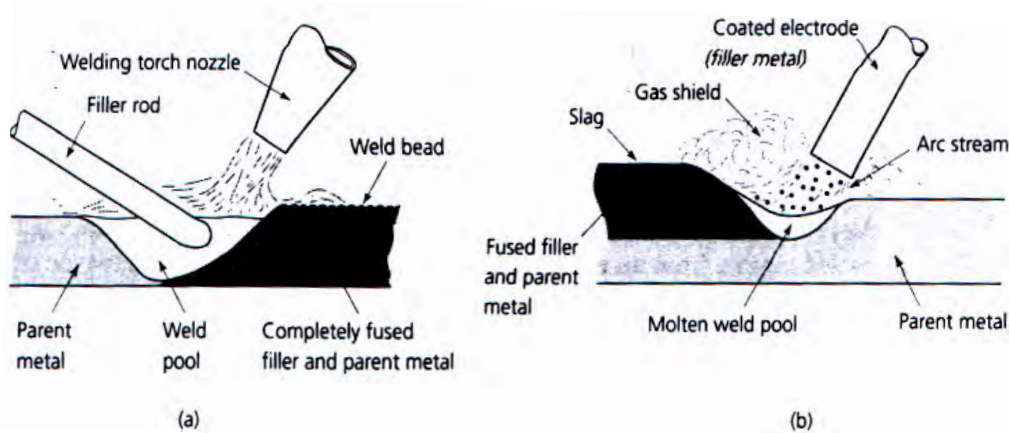


Figure 3 Comparison of (a) oxyacetylene welding and (b) manual metallic arc welding.

As with gas welding, arc-welding equipment must not be used by untrained persons except under the closest supervision.

2. Solid-phase welding

In this method the material which are welded dose not fusion, it use an out pressure to weld so it is not using any external material in the welding process.

There are several ways to weld in the solid-phase welding such as spot welding , seam welding, cold-pressure welding and friction welding etc...

Effect of welding on the structure and properties of materials:

The structures in a welded joint range from the wrought structures of the parent metal to the cast structures of the weld itself, all of which will have been subjected to heat treatment by the high temperatures involved in the process. The *weld deposit* will possess a typical cast structure with all its inherent defects. The *heat-affected-one* of the parent metal will exhibit the effects of *heat treatment*. The unaffected regions, where the temperature has not been so high, will retain

the original wrought structure of the parent metal. Therefore the effects of welding can be studied under the following headings:

- The weld-metal deposit.
- The heat-affected zone.

1. *The weld-metal deposit*

As previously stated, the weld metal can be considered as a miniature casting which has cooled rapidly from an extremely high temperature. Long columnar type crystals may be formed giving rise to a relatively weak structure, as shown in Figure 4 (a). In a multi-run weld each deposit *normalises* the preceding run and considerable grain refinement occurs with a consequent improvement in the mechanical properties of the joint, as shown in Figure 4 (b).

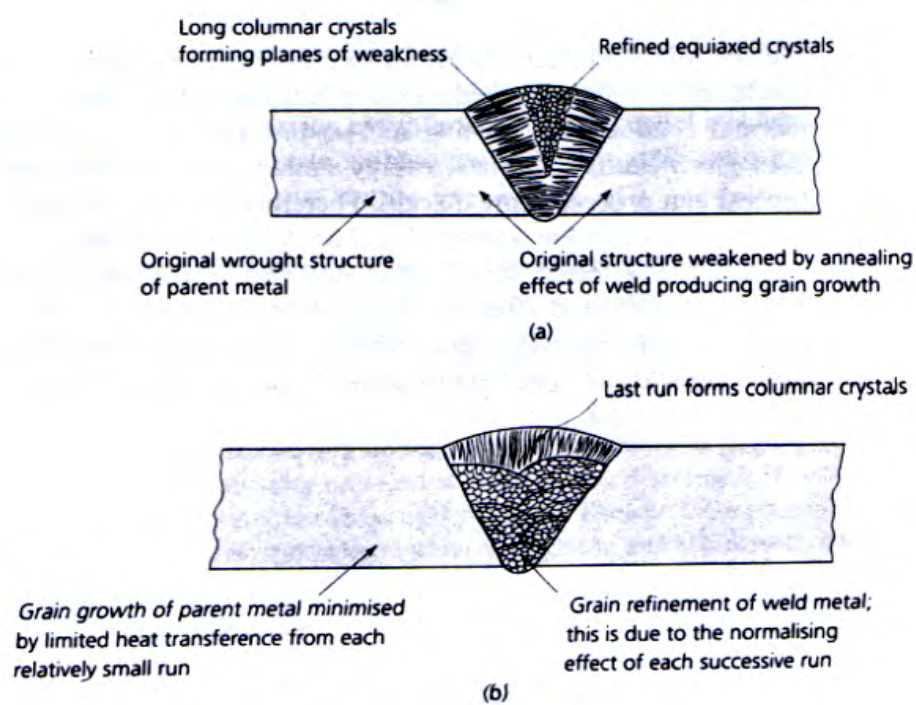


Figure 4. Weld metal deposit structure: (a) large single-run weld; (b) metallic arc weld.

Non-metallic inclusions

The formation of oxide and nitride inclusions due to atmospheric contamination is reduced by the blanket of burnt gases (products of combustion) in the case of gas welding, and by the use of a flux when electric arc welding. Modern flux-coated electrodes usually provide good quality weld deposits free from harmful inclusions. In the argon arc-welding process the metal is deposited under a shroud of the inert gas argon. This prevents oxidation and the formation of nitrides, so no flux is necessary. Further, since no flux is required there will be no slag inclusions. In multi-run welds using coated electrodes the slag must be removed between each run.

Gas porosity

The chief cause of gas porosity is the presence of hydrogen in the weld metal or the formation of steam from the reaction of hydrogen with any oxide present in the molten parent metal. In addition, hydrogen is present in the welding flame when gas welding and in the flux coatings of electrodes when arc welding.

Weld-metal cracking

Welded joints that are prepared under restraint are liable to intercrystalline cracking in the weld deposit due to contractional strains set up during the cooling of the metal. Such cracking, usually known as 'hot cracking', is largely related to the grain size and the presence of grain boundary impurities. At high temperatures, the grain boundaries are more able to accommodate shrinkage strains than the grains themselves. A coarse grain deposit with large columnar crystals possesses a relatively small grain boundary area and is, therefore, more susceptible to hot cracking.

2. The heat-affected zone

The heat-affected zone of the parent metal is difficult to define. It will depend upon such factors as:

- The temperature of the weld pool.
- The time taken to complete the weld.
- The thermal conductivity of the parent metal.
- The specific heat of the parent metal and the dimensions of the parent metal.
- The method of welding used.

Welded joints produced in metals such as copper and aluminum that have a high thermal conductivity will have a wider heat-affected zone than a plain carbon steel that has a lower thermal conductivity. Metallic arc welding produces a more concentrated heating effect than gas welding. The heat energy output is greater with arc welding, so the welding process can proceed more quickly. Therefore the heat-affected zone when arc welding will be narrower than that when gas welding the same materials.

The heat-affected zone in mild steel plate can exhibit various structures. These range from an overheated structure for those parts adjacent to the weld pool and, therefore, heated to well above the upper critical temperature, to those parts whose temperature has hardly risen above room temperature. These are shown in Figure 5 for both a single-run oxyacetylene weld, and a single-run metallic arc weld.

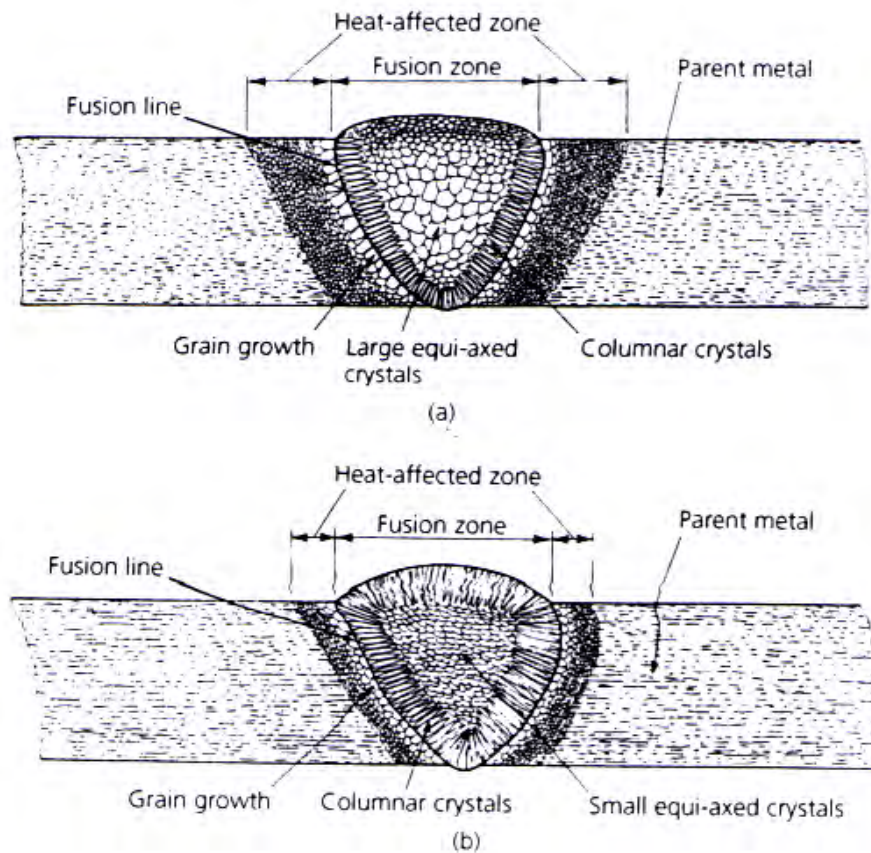


Figure 5 Macrostructure of single-run welds in mild steel: (a) oxyacetylene weld; (b) metallic arc weld.

The properties of the material will change with these changes in structure. The coarser grains will show greater ductility and softness but reduced strength. The finer crystals will show less ductility but greater hardness and strength. These effects become more apparent as the carbon content of the steel increases.

Engineering Materials

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Modes of Failure Analysis

Introduction:

- Allowable working stress

Although we describe many methods of testing on the materials, the materials may also still fail in service, sometimes with disastrous results (e.g. when the failure occurs in aircraft, bridges, ships, etc.). To try to avoid such disasters occurring, the designer avoids using materials continuously at their maximum allowable stress. This is done by employing a *factor of safety*. Unfortunately, increasing the strength of a component in the interests of safety not only increases the initial material costs, but also the operating costs.

- Failure of materials in service

It is essential that engineered products are designed in such a way that any stresses that are encountered in service are insufficient to cause failure. We have already looked at the need to introduce a *factor of safety* where the design stress does not exceed 50 % of the yield stress.

However, despite such allowances, components still fail in service and designers now recognize that operating conditions produce brittleness, fatigue, creep and /or environmental attack which, if ignored, will ultimately lead to failure. For instance, during the Second World War, cargo ships were being built quickly and cheaply using welded construction in place of the traditional riveting. A disturbing number of these ships broke up under storm conditions in the North Atlantic despite being correctly stressed. It wasn't known at that time that the cold - near arctic - conditions of the Atlantic winter caused embrittlement and failure of welded joints in the materials then being used.

1. Creep

Creep is a phenomena usually occurs at elevated temperatures since slip in the lattice structure is easier at such temperatures. Since creep leads to dimensional change, it becomes an important design factor in steam and gas turbines. The materials selected for the rotor and stator turbine blades must be carefully chosen to minimize this effect. It would be catastrophic if the rapidly rotating blades of the rotor touched the stator blades due to dimensional change through creep.

So creep can be defined as the gradual extension of a material under a constant applied load. It is a phenomenon which must be considered in the case of metals when they are required to work continuously at high temperatures. For example, the blades of jet engines and gas turbines. Figure 1. shows a typical creep curve for a metal at high temperature. A constant tensile load is applied to a test piece in a tensile testing machine whilst the test piece is maintained at a constant elevated temperature.

The creep curve obtained from this test shows three distinct periods of creep.

- **Primary creep** This commences at a fairly rapid rate but slows down as work hardening (strain hardening) sets in and the strain rate decreases. It can be seen from Figure 1. that the extension due to creep is additional to the instantaneous elongation of material to be expected when any tensile load is applied. For calculating creep as a percentage elongation, the initial elongation is ignored and creep is considered to commence at point A on the curve.
- **Secondary creep** During this period of creep the increase in strain is approximately proportional to time. That is the strain rate is constant and at its lowest value.
- **Tertiary creep** During this period of creep the strain rate increases rapidly, necking occurs and the test piece fails. Thus the initial stress, which was within the elastic range and did not produce early failure, did eventually result in failure after some period of time.

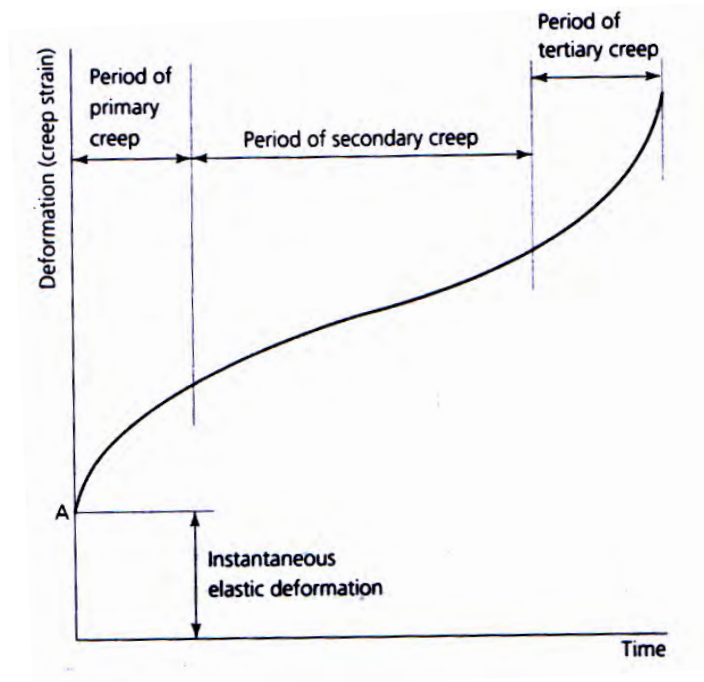


Figure 1. Creep.

Creep, for all materials, is calculated in the same manner as elongation when associated with a tensile test. That is:

$$\text{creep \%} = \frac{\text{elongation}}{\text{original length}} \times 100$$

The difference between the elongation determined from a tensile test and the creep for the same material is that the former reflects the immediate response of the material to the applied load, whereas the latter reflects the response of the material after the load has been applied for a very long period of time. (This can be several thousand hours).

2. Fatigue

Since more than 75 % of failures in engineering components are attributed to *fatigue failure*, and as the performance from engineering products is continually increased, the need to understand the failure of materials from fatigue becomes increasingly important.

In service, many engineering components undergo between thousands and millions of changes of stress within their working life. A material which is

subjected to a stress which is alternately applied and removed a very large number of times, or which varies between two limiting values, will fracture at a very much lower value of stress than in a normal tensile test. This phenomenon is referred to as fatigue failure.

It can be seen to be a particular case of brittle fracture where failure occurs under conditions of repeatedly changing stress. The change can be in magnitude, direction or both.

The source of these alternating stresses can be due to the service conditions of the component - for example, the flexing of the valve springs in a car engine, or the vibration of the axles of a vehicle caused by irregularities in road surfaces. The fatigue crack which ultimately causes fatigue failure usually starts at a point of stress concentration such as a sharp corner (incipient crack), a tooling mark due to machining with too coarse a feed, or a surface crack due to faulty heat treatment. Also for example the Aircraft wings and rotating shafts are examples of members subjected to alternating stresses, and where similar stresses are to be encountered careful consideration at the design stage and during subsequent maintenance is extremely important if fatigue failure is to be avoided.

Most fractures which have occurred due to fatigue have a distinctive appearance, as shown in figure 2. The point of origin of the failure can be seen as a smooth flat elliptical area. Surrounding this is a burnished zone with ribbed markings. This is caused by the rubbing together of the surfaces of the spreading crack due to stress reversals. When the cross-section of the component will no longer be able to carry its designed load and fail suddenly, leaving a crystalline area visible as shown in figure 2.

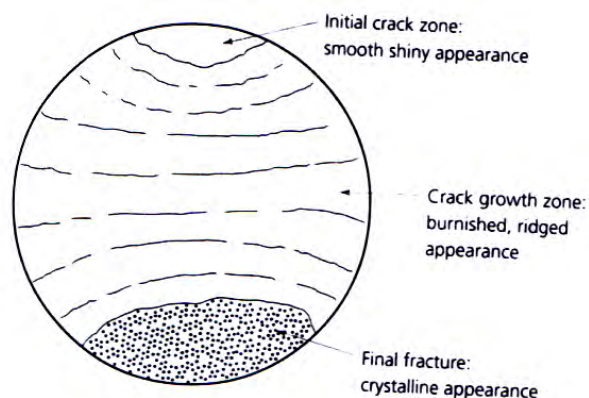


Figure 2. Appearance of fatigue failure.

The stages of fatigue failure are shown in figure 3. The fracture always starts from a point of stress concentration caused by a discontinuity such as:

- Poor surface finish.
- A crack.
- A machining mark.
- An inclusion (foreign particle) in the metal.

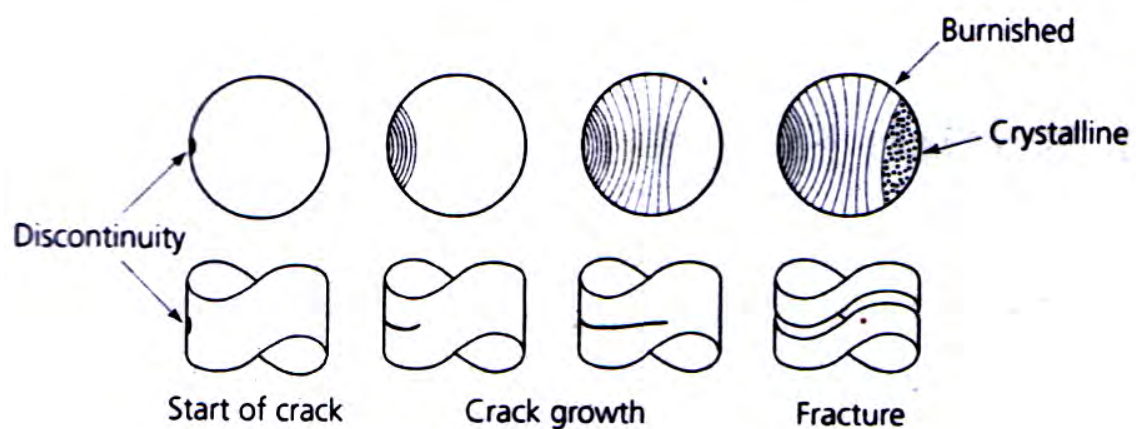


Figure 3. The stages of fatigue failure.

Factors affecting fatigue :

- As metals

Many factors affect the fatigue resistance of metals but the most important are below:

Design, surface finish, temperature, residual stresses and corrosion.

- As polymers

While the factors that affect the fatigue of polymers are:

Temperature, environment and strong sunlight.

3. Fracture

Fracture can be classified either as brittle fracture or ductile fracture, and depends upon the stress at which it occurs in relation to the elastic plastic properties of the material. This is shown in Figure 4.

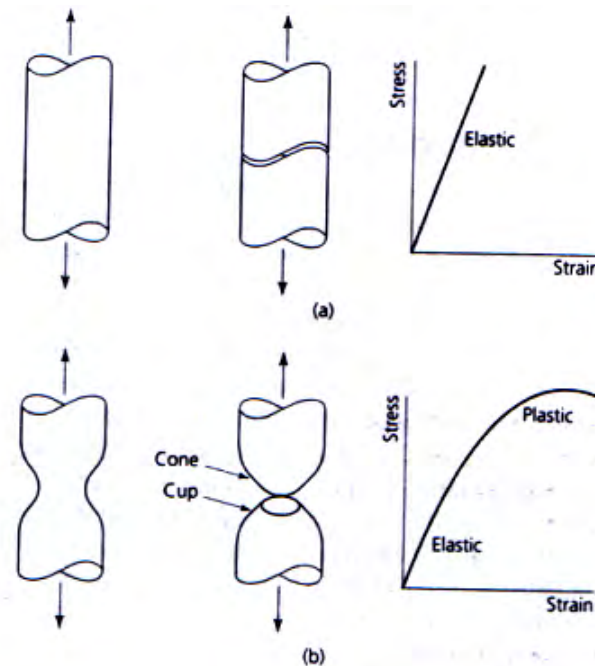


Figure 4. Types of fracture: (a) brittle; (b) ductile.

In *brittle fracture*, as shown in figure 4(a). failure occurs suddenly and before any appreciable plastic deformation takes place. The fracture follows the paths between adjacent crystal planes. Brittle fracture generally occurs in materials with the weakest atomic bonding, such as cast iron, glass and concrete. Metals with body-centered-cubic and close-packed-hexagonal structures are also susceptible to brittle fracture. Brittle fractures usually start at some discontinuity in the material or component which results in a point of stress concentration. This is not always the case and the 'pitting' caused by corrosion, for example, can also act as 'stress raiser' in the metal.

Ductile fracture takes place at some stress figure above the yield point of the material so that some plastic flow precedes failure. The resulting fracture is of the 'cup and cone' variety shown in figure 4(b), It is associated with face-centered-cubic crystals such as those found in low-carbon steels. This type of fracture occurs in destructive tensile test.

Since the fracture occurs in the plastic zone of the tensile test curve, it is obviously the result of a design fault or severe overload. As previously stated,

the maximum working stress should not exceed 50 per cent of the yield stress for the material, let alone reach the stress levels required to produce plastic deformation.

The type of fracture produced is dependent mainly on the nature of the material and its particular lattice structure. However, other factors can also influence the onset of fracture, for example:

- The rate of application of stress.
- Environmental and temperature conditions (our previous example of ships breaking up in the North Atlantic).
- The amount of cold working the material has received during any previous processing.
- The shape of the component and whether or not it has sharp corners and sudden changes of section.
- The surface finish of the components (machining marks are incipient cracks (stress raisers)).

4. Corrosion

Corrosion and its prevention has been introduced in earlier lecture. The selection of materials that are corrosion resistant is an important design consideration. The conditions encountered by materials used on site or in the hostile environment of a chemical plant are quite different to those encountered in a domestic or office situation. It would be uneconomic to use the same level of corrosion resistance and anti-corrosion coatings in all these situations. Each application must be considered on its own merits.

Many of the problems associated with 'body-rot' in cars immediately after the Second World War have been eliminated by better design to allow drainage and ventilation of hollow box section members. Also anti-corrosion treatment of the body panels before painting, and the use of improved paint systems, have all added to the improved life of car bodies. Changes in materials have also helped, with the use of high-impact polymers in those areas most susceptible to spray and salt during winter motoring. Continuous adhesive bonding has also eliminated the crevices left by spot welding, bolting and riveting.