
UNIT 1 CLASSIFICATION OF MATERIALS

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1.1 INTRODUCTION

One of the first methods of classification of materials relies on their obvious property, namely that there are three states of matter: solids, liquids or gases. This classification is so easy that it seems a pretty obvious one. We feel very confident in thus categorising materials and the classification has its uses. Solids retain their shape under normal conditions of pressure and temperature; liquids take the shape of the vessels in which they are contained. In both cases one can talk of a definite volume of the material. In gases, however, the volume of a gas is a function of the pressure and the volume of the gas and its pressure have a dependence on temperature. Properties of the gas such as internal energy, specific heat etc. are parameters that one has to measure at constant pressure or constant volume!

You will notice that classifying materials in this fashion has an advantage that some properties are so different that these form the distinguishing features. So one would never use a liquid to build a wall or use a gas for a building foundation! The usage of the material clearly defines some inherent property and a specific material is used for a specific purpose.

In Materials Science, however, we are dealing with solid bodies and the above classification is not useful. The question now is how to classify materials which are solids. Can we classify solids in terms of their physical properties such as colour, shape, electrical or mechanical behaviour? What is the use of this classification? Does it give us a better understanding into why specific materials behave as they do?

Objectives

In this unit we will see that, a useful classification of materials is as metals, ceramics and polymers. We will also see that such a classification helps us to predict the behaviour of materials in external conditions such as temperature, mechanical stress, electrical field etc. It will also help us in the selection of materials for a given application.

At the end of the unit, you should be able to :

- classify engineering materials,
- understand the classification of materials in terms of metals, ceramics and polymers,

- distinguish between the atomic or molecular forces in each class at a microscopic level,
- learn about other useful classifications of materials, and
- appreciate the new developments in materials arising out of overlapping of properties, which were thought to be characteristic of a single class.

1.2 SIMPLE CLASSIFICATION OF MATERIALS

In this section, we will discuss some methods which have been used to classify solids. You can immediately appreciate that classification in terms of colour, shape or texture has very little use. It does not give any definite information of the internal structure of the material and gives us no clue about how the material will behave in practice when it is subject to external forces. A simple classification of materials can be done according to where the materials originate. We use materials which originate from trees and plants. Examples are cotton, jute, rope as well as artefacts made from leaves such as the traditional eating plates. We also use materials such as leather, milk, silk etc. which have an animal or living being origin. And, of course, there are many materials which originate from the earth such as clay, mud, and materials refined from the ores such as the metals. We know from experience that materials from the plant and animal origin are not as hard as metals but are tougher and can withstand shock. The weathering of such materials is faster than metals and they cannot withstand very high temperature. Knowledge of the origin does in a way help us to determine the type of use that the materials can be put to.

Example 1.1

Did you play a game called animal, vegetable or mineral? This was a popular game on BBC radio, and it involved guessing the object by asking 20 questions about its behaviour under various situations. The answer to the questions would either be yes or no. Classify the following under animal, vegetable and mineral: wood, cheese, brick, stone, cloth, silk, soap, rubber. Can you think of some other method of classification which might be more appropriate?

Very often the classification relies on some obvious property; magnetic and non-magnetic, conductor and insulator, transparent and opaque, light and heavy, strong and weak etc. The main reason behind such classification is the ability to predict the behaviour of the material when it is subjected to an external force. To give an example, under a shear stress, solids show resistance or ability to withstand an external force, while liquids and gases show easy deformability. That is a reason why the latter two states are often clubbed together and termed as fluids. So when one classifies a material as a solid, one can reasonably predict its behaviour under a shear stress. Classification, therefore, is meaningful only when it helps us to understand the behaviour of materials under outside forces or fields.

1.2.1 Natural and Man-made

It is more convenient to classify materials according to whether they occur in nature or have to be made. Materials can then be classified as "naturally occurring" and "man-made" materials. Naturally occurring materials can be further classified as organic and inorganic materials. Wood and stone are natural materials, while steel and paper are man-made. Clay and cement are both inorganic materials but the first is a naturally occurring material but the other is man-made.

Materials, in the context of Materials Science and Engineering, are substances from which something useful is composed or made. Man has used them generally for the improvement of his standard of living and the ability of a society or nation is often measured by the materials it uses. Research and development of materials involves an understanding of the internal structure and correlating this with the properties of the material. This is the main preoccupation of the discipline of Materials Science and the materials scientist works at new methods of processing of materials so that the product can have the desired properties. To give an example, alloying silicon with steel gives a material with superior magnetic properties. This silicon steel is used in transformers as the core material. If silicon steel is cold drawn, i.e. drawn into sheets without heating it, the grains (which are regions in the material in which the atoms have a regular arrangement) get aligned in the direction of rolling. The resulting product, called grain-oriented-silicon-steel, is a much better material for transformer applications. Materials engineering, on the other hand, deals with the use

of appropriate materials, following cost effective methods of production to make products needed or desired by society. There is no clear cut **line** of demarcation between materials science and engineering and that is why modern syllabi in engineering contain both these ideas. So, one should know about all the existing materials, i.e. all the materials which occur **naturally**, as well as how new materials can be made.

One realises that solids are composed of **atoms** or ions and one **speaks** of a solid as an **interplay** between ions (i.e., the nucleus and core electrons) and the outermost or bonding electrons. The classification of **materials** is done in some of the following ways. A primary method of classification is in **terms** of the ordering of the **atoms** or ions. An ordered solid has its **atoms** or ions regularly **arranged** and each atom has a **definite** number of **neighbours** located in **specific** three-dimensional positions. Solids are then classified in terms of being crystalline (in which, on a **large** scale, **atoms** show **complete** ordering), or amorphous (in which materials show full disorder). Naturally occurring **materials** can be purely crystalline, such as diamond and rock salt, or **amorphous** such as skin and hair. Man-made **materials** also show both these properties, **crystallinity** such as in metals like iron or copper and amorphous **nature** such as in glass or in **many** polymeric materials. So, a **classification** such as naturally occurring **as** against **man-made**, is **not** useful in understanding the **internal** structure of **materials** but a classification as crystalline and amorphous looks to be better. However, many of the current day **materials** are partially crystalline and partially amorphous, such as cement and glass ceramics. In these materials an amorphous solid is dispersed in a crystalline matrix or the other way around. Classifying materials into amorphous and crystalline would therefore have limited use, but let us expand on this **idea**.

1.2.2 Amorphous and Crystalline

Metals are generally **crystalline** and glasses are **amorphous**. It should be noted that liquids and gases do **not** show any ordering on an atomic scale. Though not obvious at present, this classification is useful in the **processing** of materials. **Amorphous materials** are generally cooled very rapidly, while **crystalline materials** are processed more slowly so that the **atoms** have sufficient time to occupy their **respective** positions. So, if you want to make a **material** amorphous, the clue is to heat the **material** till it **melts** and then cool it as rapidly as possible from its liquid state to the solid state. On the other hand, if you want to make the material **more crystalline**, then the processing should be very slow indeed. To give an **example**, single crystal silicon is **often** grown at the rate of a few **millimetres** per hour (and this too is supposed to be rapid for single crystal growth!), while amorphous **polymers** are drawn into sheets at the rate of a few **metres per second**!

This classification does not help when we consider **categorising materials** in terms of grouping of properties. **Both** kinds of solids can show optical transparency or opaqueness; both show **ferromagnetic** ordering or **similar** electrical conductivity. The only difference in the two cases is that the properties of **amorphous** solids show **greater** variation with time than crystalline ones. This has **enhanced** the belief that the **amorphous state** is a metastable state and gradually, over an **extended** time in **many** cases, the **material** goes over to the **crystalline** state. And yet, today, we have been able to use, with **advantage**, some amorphous solids. Glass forms a **major material** for widespread use ranging from test-tubes to window panes to **television screens**. In amorphous ferromagnets we have been able to make some really good permanent **magnets** as well as some very good magnetic shielding materials. Single **crystals** (or **materials** which show perfect atomic ordering throughout the bulk) also have **important applications** such as **diamond** for cutting or for measuring the **hardness** of materials, optically active crystals such as **calcite**, laser crystals such as ruby etc. So the large scale **arrangement** of atoms does show significant property differences, and we should be able to process **materials** to take advantage of these features. But what is the scale over which materials can be considered to be ordered? We know that **one** can have perfect disorder as in **glass** over **lengths** of tens of metres (large glass sheets are routinely made and polymers like polyethylene are drawn into sheets that may be **kilometres** long!). Do we have perfect **ordering** over say a metre **length**? As we shall see, this is certainly possible but very difficult to achieve in practice. It is more **common** to grow single **crystals** of a centimetre **length** and in **engineering** materials, the scale of **crystalline** order spans over distances of a few **micrometers**!

Can we **quantify** the **amount** of crystallinity in a material? This question is **important** since, as **mentioned** above, many of today's important **materials** have **regions** of **crystallinity** and regions of amorphousness. A lump of carbon ore may be **made** of many large diamonds merged **together** and the diamond **artisan** carefully chips this **lump** so that a large piece can

be obtained. This piece has definite external shape with smooth faces. This is a characteristic of the single crystal. You can see the same feature in common rock salt or sugar crystals. Each "grain" of salt has the sodium and chlorine atoms arranged regularly in a three-dimensional array. Each grain, weighing about one thousandth of a milligram, would have more than a thousand billion ions, all regularly placed. This arrangement of ions can be "seen" using X-ray diffraction and is discussed in a latter Unit. A property of this regular arrangement is that, when a crystal is struck sharply with a knife edge, the crystal "cleaves" into two. The resulting two small crystals show the same kind of external appearance as the larger crystal. The property of cleavage is used by diamond manufacturers to "cut" the diamond appropriately so that the resulting entity gives out the maximum brilliance. A copper rod, on the other hand does not have the property of cleavage. It, however, shows a crystalline nature when subjected to X-ray diffraction analysis. So what is the difference between the atomic arrangement in diamond and in the copper rod? The difference is that in the copper rod there are a large number of "grains" or crystallites and these are randomly "glued" together. A copper rod, then, is said to be polycrystalline. Most engineering metallic solids are polycrystalline and making single crystal metals is difficult. What about a sheet of glass? X-ray diffraction shows that in this sheet the atoms do not show any regular arrangement. That is why, when glass is struck sharply, it breaks up into irregular pieces.

As can be appreciated from the discussion above, using X-ray diffraction analysis, it is possible to quantify the amount of crystallinity in a material. This is an important characteristic of polymeric materials as their mechanical properties do show dependence on the degree of crystallinity. This can be understood as follows. In a polycrystalline material there are many grains "stuck" together. In each grain there is perfect ordering and so the material has high mechanical strength as it takes a lot of energy to break up a bond. But between two crystallites there is a region of disorder called the "grain boundary" and this is a place of weakness. Materials tend to fracture at the grain boundaries. The weakness of the grain boundary is taken advantage of in studying the degree of crystallinity. If a solvent is applied to a surface of the polycrystalline material, the atoms that dissolve first would be those in the grain boundary as they would be more loosely bound. The solvent is called an etchant and the process of etching is the first step in studying the surface of a material under a microscope. Such an analysis is called microstructural analysis. Under a microscope one can see regions which have definite boundaries and so are most probably crystalline and regions where there are no clear cut boundaries and so would be amorphous. Using image processing techniques it is now possible to quantify the amount of such phases in any engineering material.

To summarise, then, a polycrystalline material shows the presence of grain boundaries. If a material does not show grain boundaries then it is either a single crystal or it is an amorphous material. Grain boundaries generally have dimensions of the order of the wavelength of visible light and so tend to scatter light. Polycrystalline materials tend to be opaque. Single crystals as well as amorphous materials do show transparency to light. In fact, if one wants to increase the transparency of a polymer sheet, one must see that crystallisation is prevented. Also, it has been found that most corrosion in solids starts from the grain boundaries, and single crystals or amorphous materials show very low degradation by corrosion. Taking advantage of this, degradation of polycrystalline materials by corrosion has been slowed down by heat-treating the surface so that an amorphous film is formed that gives protection to the bulk.

One must realise that classification is often ambiguous. In fact, in today's world most classifications have broken down. We have been able to make materials which combine properties that did not seem to be compatible. Glass is often termed as a super-cooled liquid. But by properly cooling the glass we have been able to make a mixture of glass and a crystalline phase, the product being called a glass-ceramic! We have materials that are liquid and yet show crystalline order, such as liquid crystals used in most of our wrist watches. Further, we have made composite materials which combine glasses and metals. In spite of these complexities, a simple understanding of materials does emerge by this classification. Only, one must remember that this categorisation is, at best, a convenient method of grouping together properties, or methods of processing. Let us expand this idea.

1.2.3 Method of Processing

In man-made materials a suitable classification can be thought of which determines the method of processing of materials. There are some materials which are made from the melt

and which are cast into engineering shapes by first melting and then solidifying the melt. Metals and glasses belong to this class. But the further classification into crystalline and amorphous clearly distinguishes these two. Then there are materials which are made by a chemical reaction between constituents. **Ceramics** and polymers belong to this group. The same subsequent classification between crystalline and **amorphous** structures helps in distinguishing between them as **ceramics** are usually crystalline but polymers usually amorphous. Ceramics and polymers have another distinguishable feature; ceramics are processed at high temperatures (often higher than 1000°C) while the temperatures involved in polymer processing are generally low (less than 300°C).

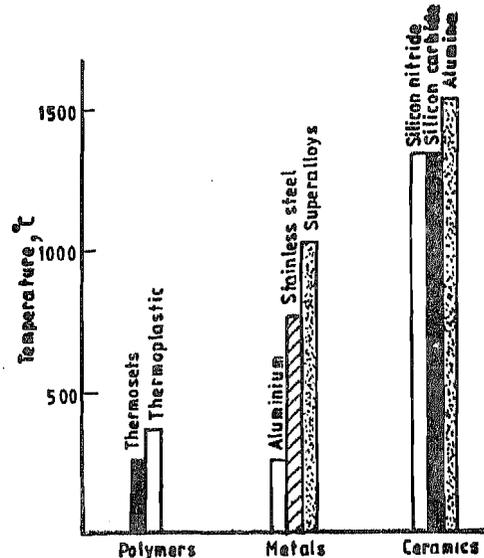


Figure 1.1 : Service Temperature Limit Indicative of Polymers, Metals and Ceramics

Metals are generally processed by melting and casting them into the required shape. The cast ingots can then be worked into other forms such as sheets or wires and are generally machineable. Ceramics are, by and large, made by a high temperature solid state reaction, without melting. The high temperature treatment, also called sintering, is carried out at temperatures as high as $1200 - 1400^{\circ}\text{C}$ and done after the material has been precast in the appropriate shape. As ceramics break easily, they are not machineable and therefore should be cast into shapes as near the finished shape as possible. Polymers are made by a chemical reaction at relatively low temperatures, generally not exceeding $100 - 150^{\circ}\text{C}$. As these are generally amorphous, like glass, they can be easily moulded into the required shape. In fact, the popularity of polymers stems from their easy processability.

It is most convenient to classify engineering materials into metals, ceramics and polymers. In this way many important properties can be clubbed together, and in Unit 3, would be shown as naturally resulting from the nature of bonding forces in solids. You must remember that in engineering materials we will include both natural and man-made materials.

Example 12

Try and classify the materials given in Example 1.1 into metals, ceramics and polymers. Don't you find this a better classification?

1.2.4 Recyclability

Let us attempt another method of classification. This is with respect to the recycling of materials. Nature has made all living things and materials bio-degradable. In this way the problem of pollution has been taken care of. The major difficulty in this is the recycling of materials or the finding of appropriate substitutes. This is a big area of research in bio-materials. In the case of man-made materials, however, the problems are of a different nature. Man uses raw materials to create artefacts that may be non bio-degradable. Take for example the case of pottery. An earthen pot outlives its civilisation and affords clues for archaeologists about the level of technology in that particular time. But today we are conscious of combating the problem of pollution and so must think about the reusability of materials.

Metals are generally recycled. Once melted they can be cast or shaped so that they can be put to the same use as before. Ceramics, once made cannot be reused. The one exception is glass which can be remelted. Its use however is limited as in the process the chance of picking up unwanted impurities is high. Plastics, today, constitute a major **pollution hazard** in the form of undisposable waste. Today's research affords us the reusing of polymer products into secondary products, which are generally of a less stringent **requirement**. All this discussion should enable us to properly make a choice depending upon the social concerns and natural resource availability.

SAQ 1

- i) How many **atoms** of silicon are there in a chunk of silicon weighing 0.5 kg ?
- ii) A wafer of silicon on which integrated circuits are deposited normally is a single crystal of diameter 100 mm and thickness 0.5 mm. How **many** atoms does this wafer contain ?
- iii) Assuming the atoms to be perfect **incompressible** spheres, how many atoms would comprise the wafer thickness ? The atomic weight of silicon is 28.1 and its density is 2.33 mg/m^3 . (Note that 1 mg/m^3 is equal to 1 gm/cm^3 .)

SAQ 2

Can the same **material** exist in crystalline and **amorphous** form? Give examples.

SAQ 3

In terms of performance, hygiene and recyclability, which material is appropriate to use as a cup for **drinking** tea ? Use your ideas to choose from

- i) polystyrene cup,
- ii) wooden cup (as done by the Japanese),
- iii) glass,
- iv) stainless steel, and
- v) **earthenware** cup (as used in our villages).

1.3 METALS, CERAMICS AND POLYMERS

From our experience, we distinguish metals by their characteristic lustre or shine. They also have high ability to conduct electricity and heat. Nearly 80% of the elements listed in the periodic table are metals. Metals possess simple crystalline **arrangements** of atoms. Polymers are generally organic in nature and comprise large molecules, with carbon and hydrogen being major constituents. Along with rubber, one includes wood, hair, skin, paper etc. in this class. Ceramics are a little more difficult to envisage. These are generally inorganic compounds of metals and non-metals. Minerals, glasses, pottery, cement, stone comprise members of this class.

Let us now see some of the common properties which exist in each class of materials. In order to see the differences clearly we will consider the way in which these materials respond to external stimuli.

1.3.1 Metals and Alloys

We are most dependent, probably on this class of materials, and the advances in early civilisations greatly depended on the ability of artisans to **make** use of metals and alloys. Beginning with iron, the second most abundant metal in the earth's crust, we have now **learnt** to use **specific** metals and alloys for specific purposes. We use copper for electrical conduits, and as **this** has become expensive, have learnt to replace it **with aluminium**. Our monetary bases, the coins, are also valued by their metal content. It is **only** because these too have become expensive that we have begun using paper currency (and there is talk **about** replacing paper with the more durable plastic !). A metal as **refined** from its ore, is hardly ever pure. It contains some unwanted and some desirable "alloying" elements. An alloy is a **combination** of two or more metals. This term is also used for a combination of a metal and a non-metal. You should **distinguish** between **an impurity in a metal and a metallic alloy**. Most engineering metals contain impurities but **an alloy is a mix** of metals in a desired proportion. **This** proportion is often given as weight percent, To give a simple example, pig-iron, the **material** obtained by reducing and melting iron ore contains the following impurities: carbon (3.0 to 4.5%), manganese (0.15 to 2.5%), silicon (1.0 to 3.0%), sulphur (0.05 to 0.1%) and phosphorus (0.1 to 2.0%). Steel, which is considered to be an alloy, is made essentially by **oxidising** pig iron to decrease **the** contents of **these** impurities and especially **carbon**. **The amount of carbon in the final product** specifies the type of steel; **thus** low carbon steels have **less than** 0.30% carbon, **medium** carbon steels contain 0.30% to 0.80% carbon and high carbon steels have **more than** 0.80% carbon. **The alloying elements** impart **the material** with special properties. For example, commercial grade iron is alloyed with nickel; 2 to 5% nickel as addition in **the alloy** increases toughness and impact resistance; 12 to 20% **alloying** increases corrosion resistance; 36% nickel alloy with iron is called **invar**, an alloy with zero thermal expansion coefficient; and a 80% nickel iron alloy has high magnetic permeability and is called **permalloy**.

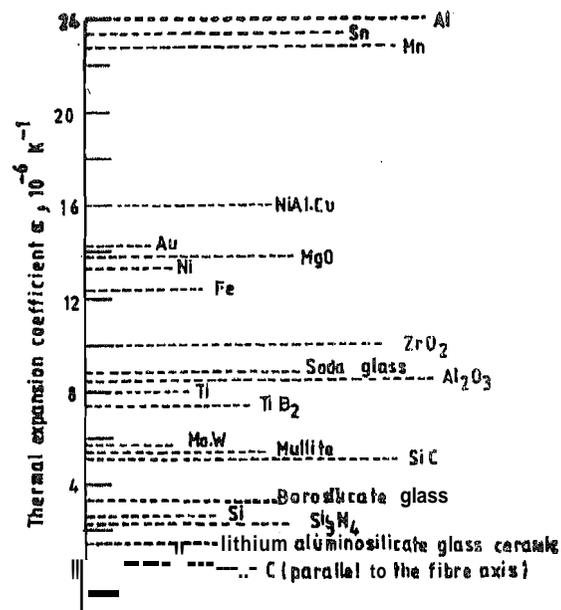


Figure 1.2 : Thermal Expansion Coefficient of Some Metals

Metals show ductility (ability to be drawn into wires) and malleability (ability to be rolled into thin sheets). For smaller tensile or stretching forces, metals are elastic, i.e., regain their original size once the force is removed, while for larger forces they are plastic, i.e. they do show deformation (permanent change of shape or elongation). Every deformation increases the **strength** (called cold working) and metals can **withstand** large forces before they **fracture**. The strain before fracture can be a few **parts** per hundred. The strength of a metal is often determined as **the** stress required to **strain** the metal by 0.2%.

Metals are generally good conductors of electricity and that is why are used in the connection of electrical circuits. In metals the electrical resistance increases with temperature in a nearly linear **manner**. This **property** helps us to make use of some metals (notably **platinum**) for measuring the temperature. In **alloys**, however, the electrical resistivity has a more complex behaviour. And as mentioned above, one can make alloys

in which the resistance is independent of temperature as in invar alloys. Invars are mostly used in designing test and measurement instruments requiring a high degree of accuracy.

Metals are crystalline when prepared using conventional methods. The atomic arrangement prefers each metal atom to have as many neighbours as possible. This means that metals have generally high densities. In the majority of cases metals show cubic symmetry of atomic arrangement. The metallic bond is difficult to visualise in a simple manner but is often pictured as a bond formed between all the metal ions which are embedded in a "sea" of electrons. We will discuss more of this in a latter Unit when we deal with bonding in solids. Metals combine to form alloys, wherein one element may show ordering whilst the other does not, or they form compounds wherein both the constituents show long range ordering.

Metals are usually subdivided into ferrous and non-ferrous metals. Ferrous metals and alloys are those which contain iron as a main constituent. Examples are steels, cast iron, iron-containing magnetic alloys etc. The most important non-ferrous metals are copper and aluminium. You can see that this classification reflects the large scale use of these materials; ferrous alloys are used primarily in the making of construction materials while non-ferrous alloys have other functional uses as electrical conductors, thermal conductors or as plating materials. It is also because of the response of iron containing materials to the environment that this classification is useful. Elaborate precautions are required to prevent iron from rusting. Alloying it with other materials is a popular method, but plating is also done to prevent corrosion. Corrosion in non-ferrous materials is not as rampant. Non-ferrous alloys are the materials which give high temperature and high pressure usability. Also because the latest developments in strong materials involves the search for light weight materials and such materials are alloys of the elements in the upper rows of the periodic table such as beryllium, boron, lithium etc. The metallurgy of these light and strong alloys is quite different from that of steel.

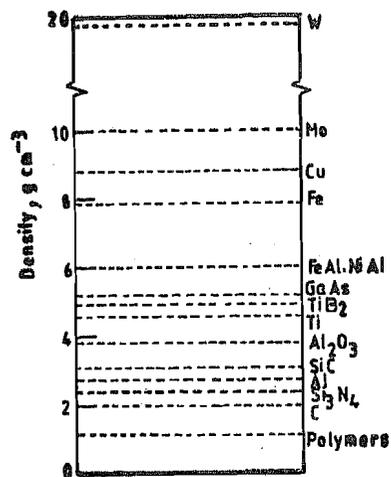


Figure 1.3 : Density of Some Materials

1.3.2 Ceramics and Glasses

Ceramics are brittle and do not, in general, show plastic deformation. They cannot be drawn into wires or beaten into thin sheets. The material easily fractures and the strain before fracture is less than 0.01%. It is due to the small strain at fracture that it is possible to repair broken crockery by gluing the broken pieces together; they fit very well!

Ceramics show varying behaviour under the influence of an electrical field; they can be excellent insulators, which is generally the case and insulating applications account for the largest use of ceramics. Some ceramics are semiconducting and one of the earliest semiconductor rectifiers used in early radio sets was zinc oxide, a ceramic. Many electronic ceramics show interesting conducting behaviour, sometimes even showing superconductivity. A very large research effort in recent times has been spent on the discovery of high temperature superconducting ceramics; high temperature in this context being temperatures above liquid nitrogen temperature (77 R), and the specific ceramics are definite amounts of the oxides of yttrium, barium, and copper in one class of compounds.

Ceramics are compounds of metals with non-metals. Hence one can consider the bonding as between positive and negatively charged ions. The crystal structures are in general

complex. However, the most important ceramics do show cubic symmetry. Ceramics are mostly polycrystalline, but very often contain a small amount of amorphous or glassy phase.

Though glasses are normally included into this group, they have significant differences in the methods of processing. Glasses are normally prepared from the melt, whereas ceramics are processed in the solid state by mixing the ingredients in powder form, compacting the mix and heating it to form a strong solid body. This method of processing results in the fact that ceramics show grains, grain-boundaries and pores. Glasses, on the other hand, do not show porosity and do not have any grain boundaries. As ceramics are polycrystalline, with grain sizes of the order of the wavelength of visible light, they are not transparent. In order to make them transparent, one has to use special manufacturing techniques to get grains smaller than light wavelengths and the total removal of porosity. Glass is so much easier to use for optical purposes, but being metastable cannot be used for high temperatures applications.

Like metals, ceramics are also subdivided in terms of oxide ceramics and non-oxide or nitride and carbide ceramics. Alumina, barium titanate etc. are the common oxide ceramics. Porcelain also falls in this class. Again due to our environment, oxide ceramics play a special role as they do not undergo corrosion in out of doors use. Tungsten carbide, boron nitride, silicon carbide etc. are examples of non-oxide ceramics. The latter require special methods of preparation and have very high melting temperatures. Non-oxide ceramics are generally more expensive and chosen for special applications. Most electronic ceramics are oxides.

1.3.3 Polymers and Rubbers

Polymers and rubbers show very large deformation under stress. They can undergo elongation as much as 900% before fracture. They can bend easily and in applications one normally exploits their flexibility. They also have the property that often the strain is a function of time. This appears as if the stress and strain lag in phase. This is called an elasticity and is the reason that this class of solids is useful in damping out vibrational energy.

Polymers are largely used for their ability to block the flow of current. That is why, in our houses, the electric cables are metal wires sheathed in rubber or paper. The metal can carry large currents and the rubber sheath prevents shorting.

Polymers are generally amorphous. As they contain large molecules, the bonding forces between molecules are dipolar in nature. These forces are not as strong as the ones in metals and ceramics. That is the reason why polymers have low melting points.

Polymers are further classified based on their application, into two: "plastics" and "elastomers". Plastics are synthetic materials which are processed by forming or moulding into the required shape. Elastomers are materials which show very large deformations under the application of an external force and which have the ability to regain their shape when the force is removed. Rubbers fall into this class of materials. Plastics are further divided into "thermoplastics" and "thermosetting" plastics. Thermoplastics get formed under the action of heat and they retain the shape they were formed to on cooling. These materials can be reheated and reformed a number of times without changes in their properties. Examples of such polymers are polyamides, polycarbonates, polyethylene terephthalate etc. Thermosetting plastics or thermosets are rigid three-dimensional networks with a lot of cross-linking bonds. Under the action of heat cross-linking is favoured and so these materials change their properties significantly on heating. These can therefore not be melted and reused as thermosetting plastics. Examples of such materials are phenol formaldehyde, epoxy resins, unsaturated polyesters etc.

You can see that this method of classification, i.e. metals, ceramics and polymers does convey a lot of information not only of the properties but also of the method of processing and realm of applicability.

Let us see whether there is another property with a wide range on the basis of which we can classify materials. We know that the response of a material to an electrical field can be very varied. This response can be quantified in terms of the resistance offered by a material to the flow of a current when a voltage is applied across it. A useful parameter for classification of materials is then the resistivity, which is really the resistance normalised to account for shape and size of the material. We know that metals are good conductors of electricity, i.e. their resistivity is small, generally a few microhm - cm. Ceramics on the

other hand are insulators that is their resistivity is megaohm-cm and even larger. In polymers one finds resistivities even orders of magnitude higher than that in ceramics. This property has a range of some 25 - 30 orders in magnitude, i.e. the ratio of the highest value to the lowest value may be 10^{30} ! As this property has played a major part in the development of materials science, materials are often classified using this parameter. Materials are now also classified as conductors, semiconductors and insulators. Metals and alloys easily fall into the first group as conductors. In fact it is very difficult to make a metal which is insulating! Ceramic and polymers generally fall into the insulator group. However, this classification has resulted into a new kind of material, sometimes classified under electronic materials, in which one can control the electrical resistivity by processing. Elements silicon and germanium are the primary members in this group; but the group also comprises electronic ceramics such as zinc oxide, semiconducting barium titanate and even electrically conducting polymers. These materials are at the heart of technological advances and all advanced nations have attained some degree of proficiency in the development of these materials.

SAQ 4

A specimen of steel has 0.8% C by weight. Calculate the ratio of iron to carbon atoms in this alloy. The molecular weights of iron and carbon are 55.85 and 12 respectively.

SAQ 5

A common compound of iron and carbon is Fe_3C . Calculate the weight percent of carbon in this compound.

SAQ 6

Distinguish between an alloy and a compound.

1.4 OTHER MATERIALS

To complete the classification of materials, one should also include materials with combination of properties brought about by a co-processing of different materials. We have seen that often concrete is reinforced with steel bars. The introduction of steel bars in a concrete mix during processing imparts the structure even greater strength. Similarly, glass fibres introduced into epoxy makes a material which is very versatile with applications ranging from making furniture to automobile bodies. Such materials, which are a judicious combination of two or more materials and which combine the properties of each of the constituents into a useful product are known as composite materials. This class has increased the family of materials many fold and one can now visualise the attainment of properties which were not thought to be compatible. One has made metal - metal composites, metal - ceramic composites, ceramic - polymer composites and so on. It has been expressed that if the present era has been the era of electronic materials, the future would be the one of composites!

Till now, we have also not considered the highly pure materials. We will see in a latter unit that the impurities, even in traces, can greatly influence the properties of materials under electric and magnetic fields, These effects become even more severe when one also wants to achieve miniaturisation. These ideas have resulted in a 'new' class of ultra-pure materials which are classified as electronic materials. Let us see these two classes of materials.

1.4.1 Electronic Materials

This is a special class of materials which have become of importance in the latter half of the twentieth century. With the advent of semiconductor processing the need for super-pure materials became of importance. The raw materials had to be extremely pure with impurity levels often lower than one part in a billion! Silicon has been the material of choice and technology has matured to give silicon single crystal structures with very low chemical and other crystal impurities. In these materials, generally the single crystal nature of the bulk is taken advantage of. Lately, other materials such as gallium arsenide, thin film substrate materials like gadolinium gallium garnet, lithium niobate etc. have emerged. In all these cases, the starting raw materials have to have purities exceeding 99.999%. This entails processing methods which are ultra-clean and raw material production which has to be done with great care. Planar structures have found acceptability and so one has to deal with these materials more as two-dimensional structures!

As this classification relies on geometrical considerations, it also contains metals, ceramics and polymers to start with. Amongst metals, gold is used very much and high purity gold ribbons are used to make interconnects between semiconducting structures on a substrate. Among ceramics, high purity alumina is a preferred substrate material on which other active materials can be deposited to form the required structures. Polymers such as polycarbonate and PET are also used as substrates (as substrates in magnetic recording) and new polymers which show conducting behaviour, like polyaniline, are used as sensors. Though this classification seems contrived, the main feature in this class is maintenance of chemical purity from the start to the finish.

1.4.2 Composites

The current trends in materials today is to make materials with tailor-made properties which can be used in engineering applications. Often it is required that a material have the strength of steel but also be flexible. One may also want a material as hard as a ceramic but free from its brittle nature. Combination of such diverse properties has led to the development of composites which are really a combination of two materials, a matrix and a filler.

A composite material has a chemically and/or a physically distinct phase distributed within a continuous phase. For example in reinforced cement concrete, the ceramic (cement) is the continuous phase, or matrix and the steel rods are the discrete phase, or filler. The composite generally has properties better than or different from those of either of the components. Usually the two components of a composite do not dissolve in each other and this means that one can identify the two components as they have an interface between them.

Composites are subdivided into classes depending on the nature of the matrix and filler. Depending on the matrix one can have metal matrix composites, ceramic matrix composites and polymer matrix composites. But a better classification comes from the identification of the filler phase. If the filler is particulate, or a rod or a sheet, we have particulate composite, fibre composite or sheet composite.

1.4.3 Future Trends

Future trends in materials show a deliberate attempt by engineers to mimic nature. Cellular materials are being studied and even metals are being processed to have a cellular nature. You must have already come across the use of hollow steel tubes in building construction. These possess the strength but are also economical as there is less wasteful use of the material. The material is used in its strength mode, that is it is used in compressive stress mode.

Another trend is to make materials such that even the primary classification of materials, i.e. solids and liquids is blurred. In this way new materials which are very pure and which are made up of tiny crystallites have been made. This is the new development of nanocrystalline materials. Again as the trend is towards softer and more pliable materials, the method of making begins in the liquid state, progresses to the semi-solid state in which the material is really a composite of a liquid and a solid and then freezes into a solid state. The process is called sol-gel processing. Sols and gels are the starting point of future materials when man would like to make materials which are like the muscle tissue or the human skin.

This brings us to the latest trend in materials, i.e. of **making** smart materials. These materials respond to the external **stimulus** in such a way that a signal is generated which can effect a **change** in the environment. The first **function** is called sensing and the **next** function is actuating.

1.5 CHOICE OF MATERIALS

With the possibility of so **many** materials with contrasting properties, it should now be clear that there is generally never a unique material for a given application. Today metals are facing stiff competition **from** plastics and composites and ceramics are replacing alloys in high temperature applications. How then does one select a material? As materials make up, on an average about 15% of the cost of a device, it is important that one chooses the material with care. There are some general guidelines comprising the four **P's viz.**, Performance, Production, Pollution and Price.

Performance: Our **natural** resources being limited, it is imperative that the **most** efficient material is chosen for a particular application. This is all the more **necessary** when replacing a defective material proves to be very costly as in space **applications**.

Production means that the material chosen should be available in production quantities and readily available. This would avoid costly delays in **procurement** and enable long term planning.

Pollution is the one important criterion that is now determining the usage of materials. The choice of eco-friendly materials is on the rise. It is necessary that the material used does not endanger the environment, is bio-degradable and does not lead to toxic or unwanted by-products. Also the **production and** processing does not **entail** a health hazard.

Finally, **Price** is something that dominates economic development **and** the material must be cost competitive, **With** transport costs rising, it makes great **sense** to use locally available materials and to develop local resources for the material development.

Can one then say that in areas where **one** uses metals, one **cannot** use a **ceramic** or polymer? In many cases yes, such as one uses metals for the **rails** of trains and one would not use a **ceramic** or **polymer** for this application. But many a times this may not be so clear a case. And sometimes one may have more than one material possible for the same application. But if one looks at the performance required of the material, this classification serves a purpose. Let us see how **this** is so. As an everyday example let us **take** the distribution of **milk** in an urban area. In earlier days, the milkman brought the milk to one's doorstep in aluminium cans. There was always the problem of adulteration as the **milk** cans could not be made tamper proof. Also the cans could not be sterilised. Then came glass bottles in which **milk** could be filled hygienically. And as the urban roads were good there was little breakage. But transport required care; the bottles had to be reused **and** the weight of the bottle was large. Then came polymer packs. **The main** advantage being **that** there was no breakage, unless a **sharp** instrument pierced the pack; it was light and very hygienic as it was not to be reused. The problem was that this pack was not environmentally friendly and contributed to pollution by littering. Milk these days is also distributed in paper cartons! So you see that depending on the need and conditions of service, one always has the choice of **an** appropriate material, be it metal, ceramic or polymer.

1.6 SUMMARY

In this unit you have seen **how** materials are classified. You have also seen that classification is a tool to aid us in proper selection of materials as well as in predicting how materials would **behave** in service. A good method of classification divides materials into metals, ceramics and polymers. This method helps us choose materials depending on application temperature. In Figure 1.1 we have given an indicative service temperature limit for metals, ceramics and polymers. You can see that for high temperature applications, ceramics are the materials of choice.

We **have** also seen that weight of a material can be of primary concern, especially in critical environments. In Figure 1.3 we have given indicative values of the range of densities of materials available.

All materials react to increase in environment temperature by expanding to varying degrees. This difference in thermal expansion is made use of in composites. We must also guard against internal stresses due to this expansion which may lead to material failure. In Figure 1.2, the thermal expansion coefficients of materials are indicated. Finally, in Table 1.1, we have given the typical values of fracture toughness for metals, ceramics and polymers.

Table 1.1 : Typical Fracture Toughness Values for Some Materials

Material	Fracture Toughness (in $10^6 \text{ Pa.m}^{1/2}$)
i) Metals	
Cast iron	4 - 10
Low carbon steel	~ 50
Aluminium alloys	20 - 50
Titanium alloys	50 - 100
Pure metals (Cu, Ni, Al)	100 - 300
ii) Ceramics	
Soda-lime glass	0.5 - 1.0
Magnesium oxide	~ 3
Alumina	1.0 - 3.0
Silicon carbide	2.0 - 4.0
Silicon nitride	3.0 - 5.0
iii) Polymers	
Polyethylene	1 - 2
Nylon	~ 3
Epoxy, polyester	~ 0.5

In conclusion, we can see that the classification of materials as metals, ceramics and polymers is very useful. It helps us to understand how materials are expected to behave in service environments. We can also use this classification to develop material combinations and composites, for specific applications.

1.7 KEY WORDS

- Alloy** : A combination of two or more metals or of metals and non-metals.
- Ceramic Materials** : Materials containing compounds of metals and non-metals which are compacted and densified under the action of heat. Ceramic materials are usually hard and brittle. Examples are clay products, alumina products etc.
- Composite Materials** : Materials which are mixtures of two or more materials. One of the materials is continuous, matrix and the other is discretely distributed, filler. Example are fibreglass-reinforcing material in a polyester or epoxy matrix.
- Electronic Materials** : Materials such as silicon, gallium arsenide etc. which are used in electronics and especially microelectronics. The materials can be metallic, such as ultra-pure gold, ceramics (such as semiconducting barium titanate) or polymers, such as polyanilines or polysulphones, which are semiconducting.
- Ferrous Metals and Alloys** : Metals and alloys which contain a large percentage of iron such as steels and cast iron.
- Glass** : A subset of ceramic materials but which are amorphous in crystal structure. Glasses can be silicate, borate and phosphate compounds or their combination. The metals are usually sodium (soda-glass), calcium (soda-lime glass) or lead.

Materials	:	Substances of which something is made or composed of. The term "engineering materials" is sometimes used to refer specifically to materials used to produce technical products.
Materials Engineering	:	An engineering discipline which is concerned with the use of fundamental and applied knowledge of materials so that they can be converted into products useful to society.
Materials Science	:	A discipline which is primarily concerned with the search for basic knowledge about the internal structure, properties and processing of materials.
Metallic Materials	:	Materials (metals and metal alloys) which are characterised by high thermal and electrical conductivities. Examples are iron, steel, aluminium , copper etc.
Mechanical Properties	:	(1) Stress, which is the force or load applied divided by the cross-sectional area, and has units of newtons/square meter; and (2) Strain, which is a dimensionless quantity, equal to the elongation per unit length of the material; it is sometimes given as millimetres per meter!
Phase	:	It is a region, in terms of the microstructure of the material, that differs in structure and/or composition from another region. It is a physically homogeneous and distinct portion of a material system.
Non-ferrous Metals and Alloys	:	Metals and alloys which do not contain iron as a major phase. Examples are aluminium, copper, brass, zinc, titanium, nickel, etc.
Polymeric Materials	:	Materials consisting of long chain molecules or networks of low weight elements such as carbon, hydrogen, oxygen and nitrogen. Most polymeric materials have low electrical and thermal conductivities. Examples are polyethylene, polyvinyl chloride, etc.

1.8 ANSWERS TO SAQs

SAQ 1

i) In 28.1 g of silicon there are 6.023×10^{23} atoms.

Therefore 0.5 kg of silicon would contain $(500 \times 6.023 \times 10^{23}) / 28.1$
 $= 1.072 \times 10^{25}$ atoms.

ii) The volume of the wafer is $(\pi \times 5 \times 5) \times 0.05$ cubic centimetres.

The weight of the wafer is $1.25 \times \pi \times 2.33$ grams.

The number of atoms is therefore $(1.25 \times 2.33 \times \pi \times 6.023 \times 10^{23}) / 28.1$
 $= 1.961 \times 10^{23}$ atoms!

iii) Volume of 1 silicon atom is $(28.1) / (2.33 \times 6.023 \times 10^{23})$; assuming spherical shape,

$$R^3 = (3/4 \pi) \times (28.1) / (2.33 \times 6.023 \times 10^{23})$$

The radius of the silicon atom, $R = 1.71 \text{ \AA}$ or diameter of 3.42 \AA . Therefore, in a thickness of 0.5 mm there are $0.05 / (3.42 \times 10^{-8})$ or 1.46×10^6 atoms.

SAQ 2

Yes the same material can exist in crystalline and amorphous **forms**. Carbon is a good example. Diamond is the crystalline form and charcoal the amorphous form. So also quartz is crystalline silica, while fused silica is amorphous.

Materials can also exist in more **than** one crystalline forms. Diamond and graphite is the example of crystalline carbon **forms**. **Titania** can exist as **rutile** and **anatase**. This property is **known** as polymorphism.

i) **Polystyrene Cup**

It is good for small drinks as it would be difficult for it, **mechanically**, to hold more than say 200 grams. Its thermal conductivity being poor, a drink stays hot for a long time. It is clean, and as it is for one-time use only, does not need to be washed. It is not recyclable and has been causing some concern in disposal. One cannot have any variety in colour.

ii) **Wooden Cup**

It changes the flavour of a hot drink, but one gets to like it; it is a natural material and so is environmentally friendly; the Japanese use it **many** times, but without washing and it can get stained so a person drinks from the same cup and will not share it. Wood is also a bad conductor and so a drink stays hot for a long enough time.

iii) **Glass Cup**

We use it most often for it is aesthetic and very attractively coloured. Glass is not a good conductor and is breakable; there have been many instances of **the** cup cracking when a hot drink is poured into it. It is not environmentally friendly but is recyclable in a secondary way.

iv) **Steel Cup**

Long lasting, reusable, easy to clean and non-breakable; but it is using a material with very good properties in an application which does not need these properties (steel, if stainless, is a bad thermal conductor, and stainless steel is often used in cryogenic applications).

v) **Earthenware Cup**

But for aesthetic quality, this is an admirably environmentally friendly usage; it is hygienic if meant for a one time use. This is the best "disposable" cup.

SAQ 4

In 100 **gms** the weight of iron is 99.2 **and** that of carbon is 0.8. In this weight, the number of **moles** of iron is $99.2/55.85 = 1.776$; and the number of moles of C is $0.8/12 = 0.067$. The ratio of iron to carbon is then 26.6 : 1, i.e. for **every** 266 iron atoms there are 10 carbon atoms, Or **the** mole percent of **carbon** is 3.77%.

SAQ 5

The compound has 1 mole of carbon for every three moles of iron. Therefore, for every 12 **gms** of carbon there are 3×55.85 or 167.55 **gms** of iron. The molecular weight of the compound is 179.55. Hence, weight percent of carbon is $12/179.55$ or 6.68 %.

SAQ 6

A metal alloy is a combination of two or **more** metals or a combination of one or more metal with one or more non-metals. The combination is really a mixture (as in a liquid) with one phase dissolved in **the** other. As this is a **mixture** there is a range of compositions possible. For example, in steels you can **have** **carbon** ranging from say 0 to 0.8%.

In a compound there is a definite molar proportion of the elements. In Fe_3C , for example, there is a definite ratio of the weights of the element. that would combine. The crystal structure of the compound can be quite different from the crystal structure of the combining elements; but in an alloy **the** crystal structure of the major phase is the structure of **the** alloy.