Production & Industrial Engineering

General Engineering

Vol. I : Engineering Materials

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

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General Engineering : Vol. I – Engineering Materials

First Edition : 2020

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VOLUME I

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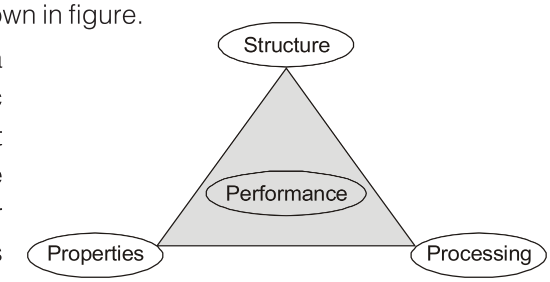
INTRODUCTION

Materials are so important in the development of human civilization that the historians have identified early periods of civilization by the name of most significantly used material, e.g.: Stone Age, Bronze Age. This is just an observation made to showcase the importance of materials and their impact on human civilization. It is obvious that materials have affected and controlling a broad range of human activities through thousands of decades.

As engineering materials constitute foundation of technology, it's not only necessary but a must to understand how materials behave like they do and why they differ in properties. This is only possible with the atomistic understanding allowed by quantum mechanics that first explained atoms and then solids starting in the 1930s. The combination of physics, chemistry, and the focus on the relationship between the properties of a material and its microstructure is the domain of Materials Science. The development of this science allowed designing materials and provided a knowledge base for the engineering applications (Materials Engineering). Important components of the subject Materials Science are structure, properties, processing, and performance. A schematic interrelation between these four components is shown in figure.



Interrelation between four components of Material Science

Innovation in engineering often means the clever use of a new material for a specific application. For example: plastic containers in place of age-old metallic containers. It is well learnt lesion that engineering disasters are frequently caused by the misuse of materials. So it is vital that the professional engineer should know how to select materials which best fit the demands of the design - economic and aesthetic demands, as well as demands of strength and durability. Beforehand the designer must understand the properties of materials, and their limitations. Thus it is very important that every engineer must study and understand the concepts of Materials Science and Engineering. This enables the engineer :

- To select a material for a given use based on considerations of cost and performance.
- To understand the limits of materials and the change of their properties with use.
- To be able to create a new material that will have some desirable properties.
- To be able to use the material for different application.

1.1 Classification of Materials

Like many other things, materials are classified in groups, so that our brain can handle the complexity. One can classify them based on many criteria, for example crystal structure (arrangement of atoms and bonds between them), or properties, or use. Metals, Ceramics, Polymers, Composites, Semiconductors, and Biomaterials constitute the main classes of present engineering materials. Following chart describes the basic classification of material:

1. **Metals :** These materials are characterized by high thermal and electrical conductivity; strong yet deformable under applied mechanical loads; opaque to light (shiny if polished). These characteristics are due to valence electrons that are detached from atoms, and spread in an electron sea that glues the ions together, i.e. atoms are bound together by metallic bonds and weaker van der Waalls forces. Pure metals are not good enough for many applications, especially structural applications. Thus metals are used in alloy form i.e. a metal mixed with another metal to improve the desired qualities. E.g.: aluminum, steel, brass, gold.

   Properties of metals :

   1. At ordinary temperature they are usually solid.
   2. To some extent they are malleable and ductile.
   3. They are usually good electrical and thermal conductors.
   4. Most of the metals form alloys.
   5. Their freshly cut surface arc lustrous.
   6. When struck they produce typical metallic sound.

Metals are typically classified according to their uses in engineering as under :

(i) **Pure metals :** They are obtained by refining the ore. Generally, it is very difficult to produce pure metal. Again, pure metals are mostly, not of any use to the engineers. But by specialized and expensive techniques, very pure metals (99.99% pure) can be obtained e.g., copper and aluminium

(ii) **Alloyed metals :** Metals are alloyed by combining two or more metals. The combination so formed is called an alloy. The properties of an alloy can be totally different from its basic metals. For example. 18.8 stainless steel, which contains 18% chromium, 8% nickel in low carbon steel (carbon less than 0.15%) is extremely tough exceedingly ductile and highly resistant to corrosion. These properties are quite different from the behaviour of original carbon steel.

(iii) **Ferrous metals :** Iron is the principal constituent of such metals. Ferrous alloys contain significant amount of non-ferrous metals. In engineering, ferrous alloys are extremely important They can be classified on the basis of the percentage of carbon and other alloying elements present. The important groupings according to the percentage of carbon present are :

(a) **Mild steels :** The carbon present range from 0.15% to 0.25%. These steels have good weldability and are moderately strong. The cost of production is low.

(b) **Medium carbon steels :** These steels contain carbon between 0.3% to 0.6%, their weldability is comparatively lesser but their strength is high.

(c) **High carbon steels :** The carbon content range from 0.65% to 1.5%. The weldability is poor and these steels become hard and tough by heat treatment.

If carbon content is up to 1.5% and silica up to 0.5% manganese up to 1.5% along with traces of other elements, the steel so formed is called as plain carbon steel.

(d) **Cast irons :** These iron contain carbon between 2% to 4%. These iron as ferrous casting alloys. The cost of production is quite low.

(iv) **Non-ferrous metals :** They are composed of metals other then iron. Non-ferrous alloys may contains iron is small proportion. Out of numerous non-ferrous metals only seven are available in sufficient quantity and at low cost. They are used as common engineering metals. They are copper, tin, lead, aluminium, zinc, nickel and magnesium. Some other metals, about fourteen in number, are produced in relatively small quantities but widely used in modern industry. These are cobalt, mercury, chromium, tungsten, vanadium, molybdenum, antimony, cadmium, zirconium. beryllium, niobium, titanium, tantalum and manganese.

(v) **Sintered metals :** These metals possess very different properties and structures as compared to the metals that they have been cast. They are produced by powder metallurgy technique. The metals to be sintered are first powdered and than mixed in calculated proportions. After mixing they are put in the die of required shape and then processed with certain pressure. Finally, they are sintered in the furnace. The mixture produced is not the true alloy but it possesses some or many properties of typical alloys.

(vi) **Clad metals :** A 'sandwich' of two materials is prepared to avail the advantage of the properties of both materials. Such a technique is called **cladding**. For examples, stainless steel is mostly embedded by a thick layer of mild steel, by rolling the two metals together, while they are red hot. This cladding technique will not allow to corrosion of one surface. This is relatively cheap to manufacture. Another example is cladding of duralumin with thin sheets of pure aluminium. The surface layers (outside layers) of aluminium resist corrosion, whereas centre layer of duralumin imparts high strength.

2. **Ceramics :** These are inorganic compounds, and usually made either of oxides, carbides, nitrides, or silicates of metals. Ceramics are typically partly crystalline and partly amorphous. Atoms (ions often) in ceramic materials behave mostly like either positive or negative ions, and are bound by very strong Coulomb forces between them. These materials are characterized by very high strength under compression, low ductility; usually insulators to heat and electricity. Examples: glass, porcelain, many minerals.

3. **Polymers :** Polymers in the form of thermo-plastics (nylon, polyethylene, polyvinyl chloride, rubber, etc.) consist of molecules that have covalent bonding within each molecule and van der Waals forces between them. Polymers in the form of thermo-sets (e.g., epoxy, phenolics, etc.) consist of a network of covalent bonds. They are based on H, C and other non-metallic elements. Polymers are amorphous, except for a minority of thermoplastics. Due to the kind of bonding, polymers are typically electrical and thermal insulators. However, conducting polymers can be obtained by doping, and conducting polymer-matrix composites can be obtained by the use of conducting fillers. They decompose at moderate temperatures (100 – 400°C), and are lightweight. Other properties vary greatly.

4. **Composite materials :** Composite materials are multiphase materials obtained by artificial combination of different materials to attain properties that the individual components cannot attain. An example is a lightweight brake disc obtained by embedding SiC particles in Al-alloy matrix. Another example is reinforced cement concrete, a structural composite obtained by combining cement (the matrix, i.e., the binder, obtained by a reaction known as hydration, between cement and water), sand (fine aggregate), gravel (coarse aggregate), and, thick steel fibers. However, there are some natural composites available in nature, for example – wood. In general, composites are classified according to their matrix materials. The main classes of composites are metal-matrix, polymer-matrix, and ceramic-matrix.

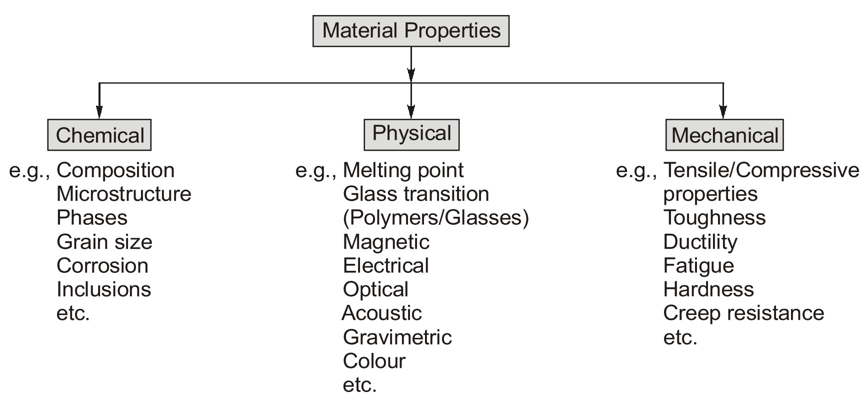
5. **Semiconductors :** Semiconductors are covalent in nature. Their atomic structure is characterized by the highest occupied energy band (the valence band, where the valence electrons reside energetically) full such that the energy gap between the top of the valence band and the bottom of the empty energy band (the conduction band) is small enough for some fraction of the valence electrons to be excited

from the valence band to the conduction band by thermal, optical, or other forms of energy. Their electrical properties depend extremely strongly on minute proportions of contaminants. They are usually doped in order to enhance electrical conductivity. They are used in the form of single crystals without dislocations because grain boundaries and dislocations would degrade electrical behavior. They are opaque to visible light but transparent to the infrared. Examples: silicon (Si), germanium (Ge), and gallium arsenide (GaAs, a compound semiconductor).

6. **Biomaterials:** These are any type material that can be used for replacement of damaged or diseased human body parts. Primary requirement of these materials is that they must be biocompatible with body tissues, and must not produce toxic substances. Other important material factors are: ability to support forces; low friction, wear, density, and cost; reproducibility. Typical applications involve heart valves, hip joints, dental implants, intraocular lenses. Examples: Stainless steel, Co-28Cr-6Mo, Ti-6Al-4V, ultra high molecular weight poly-ethelene, high purity dense Al-oxide, etc.

1.2 Engineering Requirements of Materials

The practical application of all types of engineering materials depends upon a thorough knowledge of their particular properties under a wide range of conditions. The range of properties found in different classes of materials is very large. Some of the most important properties of materials arc discussed below :



Requirement of Engineering Materials

Mechanical	:	Strength, stiffness, ductility, elasticity, plasticity, toughness, brittleness, hardness, malleability, creep, fatigue.
Electrical	:	Conductivity, resistivity, dielectric permittivity, dielectric strength.
Magnetic	:	Permeability, coercive force, hysteresis.
Thermal	:	Specific heat, thermal expansion. conductivity.
Chemical	:	Corrosions resistance, acidity or alkalinity, composition.
Physical	:	Dimensions, density, porosity, structure.
Acoustial	:	Sound transmission, sound reflection.
Optical	:	Colour, light transmission, light reflection.

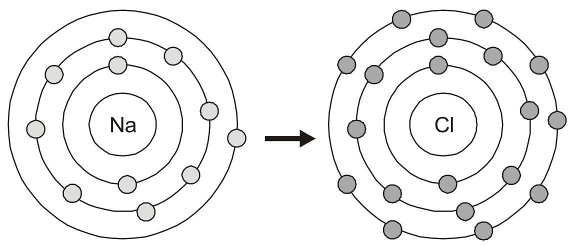
1.3 Atomic Bonds

Three different types of **primary** or chemical **bond** are found in solids – ionic, covalent, and metallic. For each type, the bonding necessarily involves the valence electrons; furthermore, the nature of the bond depends on the electron structures of the constituent atoms. In general, each of these three types of bonding arises from the tendency of the atoms to assume stable electron structures, like those of the inert gases, by completely filling the outermost electron shell.

Secondary or physical forces and energies are also found in many solid materials; they are weaker than the primary ones, but nonetheless influence the physical properties of some materials.

1.3.1 Ionic Bond

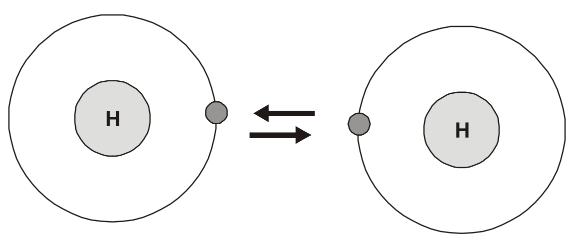
This bond exists between two atoms when one of the atoms is negative (has an extra electron) and another is positive (has lost an electron). Then there is a strong, direct Coulomb attraction. Basically ionic bonds are non-directional in nature. An example is NaCl. In the molecule, there are more electrons around Cl, forming Cl^- and fewer electrons around Na, forming Na^+. Ionic bonds are the strongest bonds. In real solids, ionic bonding is usually exists along with covalent bonding.



Schematic representation of ioning bonding. Here Na is giving an electron to Cl to have stable structure.

1.3.2 Covalent Bond

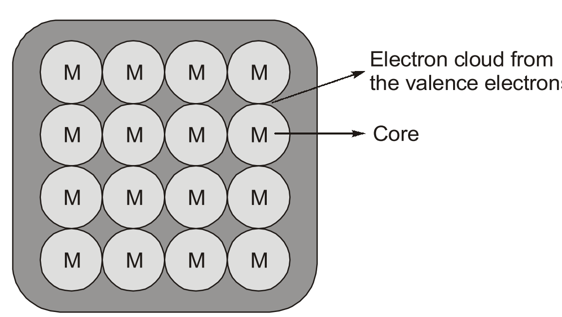
In covalent bonding, electrons are shared between the atoms, to saturate the valency. The simplest example is the H_2 molecule, where the electrons spend more time in between the nuclei of two atoms than outside, thus producing bonding. Covalent bonds are stereo-specific, i.e., each bond is between a specific pair of atoms, which share a pair of electrons (of opposite magnetic spins). Typically, covalent bonds are very strong, and directional in nature The hardness of diamond is a result of the fact that each carbon atom is covalently bonded with four neighboring atoms, and each neighbor is bonded with an equal number of atoms to form a rigid three-dimensional structure.



Schematic representation of covalent bond in Hydrogen molecule (sharing of electrons)

1.3.3 Metallic Bond

Metals are characterised by high thermal and electrical conductivities. Thus, neither covalent nor ionic bondings are realized because both types of bonding localize the valence electrons and preclude conduction. However, strong bonding does occur in metals. The valence electrons of metals also are delocalized. Thus metallic bonding can be viewed as metal containing a periodic structure of positive ions surrounded by a sea of delocalized electrons. The attraction between the two provides the bond, which is non-directional.



Metallic Bonding