Nanomaterials

2nd year Medical Physics

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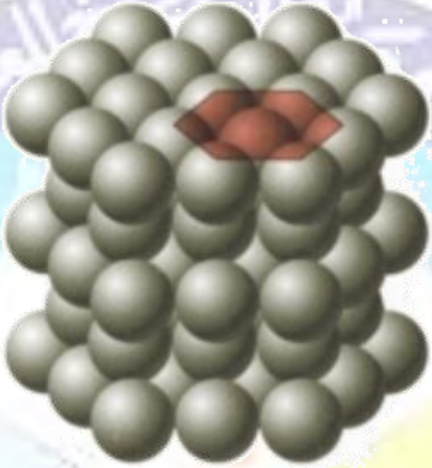
Lecture 3: Types of Materials



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2.6.2 Body-Centred Cubic Structure

Another common metallic crystal structure also has a cubic unit cell with atoms located at all eight corners and a single atom at the cube centre. This is called a body-centred cubic (*bcc*) crystal structure.

Centre and corner atoms touch one another along cube diagonals, and unit cell length a and atomic radius **R** are related through:

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

Chromium, iron, tungsten, as well as several other metals exhibit a bcc structure.

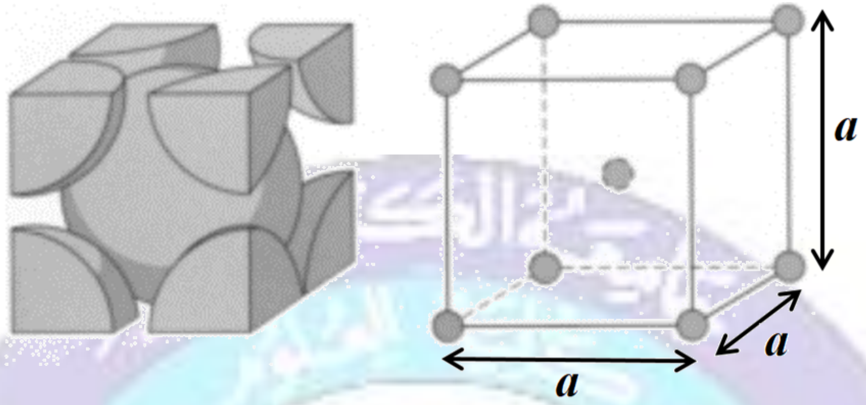


Figure 3.1 a body-Centred Cubic (FCC) unit cell

Two atoms are associated with each bcc unit cell: the equivalent of one atom from the eight corners, each of which is shared among eight unit cells, and the single centre atom, which is wholly contained within its cell.

The coordination number for the BCC crystal structure is 8; each centre atom has as nearest neighbours its eight corner atoms. Since the coordination number is less for BCC than FCC, so also is the atomic packing factor (APF) for BCC lower—0.68 versus 0.74.

2.6.3 Hexagonal Close Packed Structure

Not all metals have unit cells with cubic symmetry; the final common metallic crystal structure to be discussed has a unit cell that is hexagonal. Figure 3.2 shows a reduced-sphere unit cell for this structure, which is termed hexagonal close-packed (hcp).

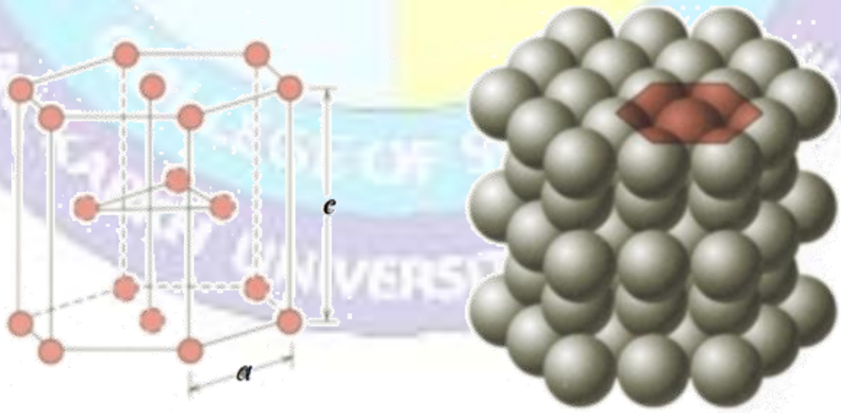


Figure 3.1 a hexagonal close packed (*hcp)* unit cell

The top and bottom faces of the unit cell consist of six atoms that form regular hexagons and surround a single atom in the centre. Another plane that provides three additional atoms to the unit cell is situated between the top and bottom planes. The atoms in this mid-plane have as nearest neighbours atoms in both of the adjacent two planes.

The equivalent of six atoms is contained in each unit cell; one-sixth of each of the 12 top and bottom face corner atoms, one-half of each of the 2 centre face atoms, and all the 3 mid-plane interior atoms. If *a* and *c* represent, respectively, the short and long unit cell dimensions, the c/a ratio should be 1.633. However, for some HCP metals this ratio deviates from the ideal value.

The coordination number and the atomic packing factor for the HCP crystal structure are the same as for fcc: 12 and 0.74, respectively.

The HCP metals include cadmium, magnesium, titanium, and zinc. The crystal structure of some of metals is listed in Table 3.1.

Table 3.1 Atomic Radii and Crystal Structures for 16 Metals

Metal	Crystal Structure[a]	Atomic Radius[b] (nm)	Metal	Crystal Structure	Atomic Radius (nm)
Aluminum	FCC	0.1431	Molybdenum	BCC	0.1363
Cadmium	HCP	0.1490	Nickel	FCC	0.1246
Chromium	BCC	0.1249	Platinum	FCC	0.1387
Cobalt	HCP	0.1253	Silver	FCC	0.1445
Copper	FCC	0.1278	Tantalum	BCC	0.1430
Gold	FCC	0.1442	Titanium (α)	HCP	0.1445
Iron (α)	BCC	0.1241	Tungsten	BCC	0.1371
Lead	FCC	0.1750	Zinc	HCP	0.1332

Materials can have atomic arrangements (crystal systems) other than cubic and hexagonal. These types are listed in table 3.2 with their main features.

3.1 Types of Materials

Solid materials have been conveniently grouped into three basic classifications: metals, ceramics, and polymers. This scheme is based primarily on chemical makeup and atomic structure, and most materials fall into one distinct grouping or another, although there are some intermediates.

3.1.1 Metals

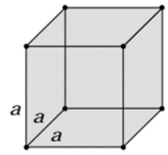
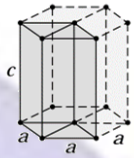
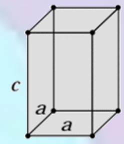
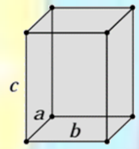
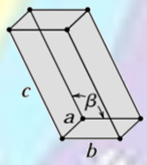
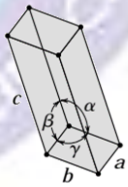
Metallic materials are normally combinations of metallic elements. They have large numbers of non-localized electrons; that is, these electrons are not bound to particular atoms. Many properties of metals are directly attributable to these electrons.

Metals are extremely good conductors of electricity and heat and are not transparent to visible light; a polished metal surface has a lustrous appearance. Furthermore, metals are quite strong, yet deformable, which accounts for their extensive use in structural applications.

3.1.2 Ceramics

Ceramics are compounds between metallic and non-metallic elements; they are most frequently oxides, nitrides, and carbides. The wide range of materials that falls within this classification includes ceramics that are composed of clay minerals, cement, and glass. These materials are typically insulative to the passage of electricity and heat, and are more resistant to high temperatures and harsh environments than metals and polymers. With regard to mechanical behaviour, ceramics are hard but very brittle.

Table 3.2 the seven atomic arrangements

Crystal System	***Axial Relationships***	***Interaxial Angles***	***Unit Cell Geometry***
Cubic	$a = b = c$	$\alpha = \beta = \gamma = 90°$	
Hexagonal	$a = b \neq c$	$\alpha = \beta = 90°, \gamma = 120°$	
Tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90°$	
Rhombohedral	$a = b = c$	$\alpha = \beta = \gamma \neq 90°$	
Orthorhombic	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90°$	
Monoclinic	$a \neq b \neq c$	$\alpha = \gamma = 90° \neq \beta$	
Triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma \neq 90°$	

3.1.3 Polymers

Polymers include the familiar plastic and rubber materials. Many of them are organic compounds that are chemically based on carbon, hydrogen, and other non-metallic elements; furthermore, they have very large molecular structures. These materials typically have low densities and may be extremely flexible.

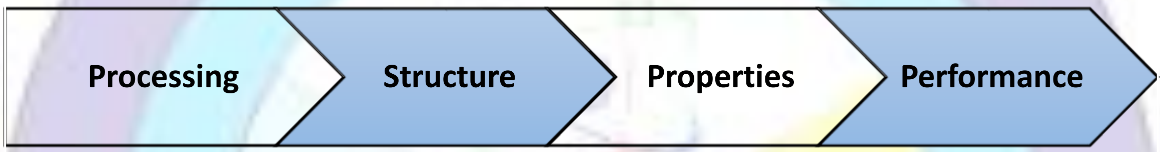
Polymers have limited electrical and thermal conductivity because of the less mobile electrons, which are essential for transferring electrical and thermal energy from one area to another. Instead, the limited conductivity is transferred through atomic vibrations.

3.2 The relationship between structure, properties and performance

One of the main objectives of materials science is to investigate the relationship that exist between the materials structure and its properties. The properties of a certain material results and is directly affected by its internal structure. The performance of that materials depends on its properties. Materials engineering builds on this knowledge to design materials with different or preferred properties.

In order to improve of change the properties of a material, a change in its internal structure must occur. On the other hand, if the service conditions alter the internal structure of a material, a change in the properties and performance of that materials is very likely to occur. For example, the gradual hardening of rubber when exposed to light.

Materials must be processed to meet the specifications that are required for the product being designed. This process is called 'Production' or 'Processing'. The processing of a part or a material is all the steps that convert an ore or a melt to a required end product with a defined shape and properties.



A countless number of materials exist nowadays, but only a small number is used. For example, there are more than 2000 types of steel, 9000 types of plastics and 10,000 types of glass. The main parameters that determine whether a material is suitable to usage are:

- The availability of its ores.
- Initial properties.
- Cost.
- Service performance.

3.3 Review of selected properties of materials

Materials are characterised by their properties, which can be grouped into categories and the most important ones are: mechanical, electrical, thermal, magnetic and optical. A couple of these properties will be reviewed in the next section.

3.3.1 Conductivity (and Resistivity)

The electrical resistance (R) of an object is a measure of its opposition to the flow of electric current. Its value depends on the material's nature and the object shape. The resistance of a wire in a circuit can be found through:

$$R = \rho(\frac{L}{A})$$

Where ρ is the electrical resistivity (Ω.m), L is the wire length (m) and A is the cross sectional area of the wire (m^2).

The reciprocal of the resistivity is known as the electrical conductivity (σ), which can be found through:

$$\sigma = \frac{1}{\rho}$$

Where σ has the units of $(\Omega.m)^{-1}$.

There is also the thermal conductivity (k) of a material, which is defined as the measure of its ability to conduct heat. It can be expressed as the power (P) per unit area (A),*i.e*:

$$k = \frac{P}{A}$$

The unit of thermal conductivity is (watt/m.k).

Note: the thermal resistivity is not the reciprocal of thermal conductivity.

3.3.2 Stress and Strain

In mechanics, stress subjected on a material is a measure of the applied force acting on that material per unit area, which can be expressed by:

$$s = \frac{F}{A}$$

and it has the units of N/m^2. Strain, on the other hand, is the dimensional response of a material to the applied stress. It has no units and it can be calculated through:

$$e = \frac{\Delta L}{L}$$

It is worth noting that the numerical value of strain has a positive sign under tensile stress, while it has a negative sign under compressive stress.

Strain in material can be elastic or plastic. Elastic strain is reversible, which means that strain disappears if the stress is removed. With elastic strain, the relationship between stress and strain of the same material is expressed by Hook's law, which denotes:

$$E = \frac{s}{e}$$

where E is the modulus of elasticity or Young's modulus, which has the units of stress.

Plastic strain occurs when the stress exceeds a critical value that initiates a permanent displacement of atoms from the neighbouring atoms.

It is suitable here to define some of the terms that are going to be used later on. These are as follows:

- **Strength** is the critical value of stress required to initiate failure.
- **Hardness** is the resistance of a material to penetration.
- **Ductility** is the permanent strain that accompanies fracture.
- **Elongation** is the amount of extension in length from the onset of stress until fracture.
- **Toughness** is the amount of energy required to cause failure in the material. It can be calculated by measuring the area under stress-strain curve.

3.4 Worked examples

1. A copper wire has a diameter of 0.9 mm:
   (a) What is the resistance of a 30 cm wire of the same material?
   (b) How many watts are expended if 1.5 volt dc are applied across 30 m of this wire? Note that ρ for this wire is $17\text{x}10^{-19}$ Ω.m.
   Solution:
   (a) $A = \pi r^2 = 3.14 \times (0.9\times10^{-3})^2$
   $$R = \rho\left(\frac{L}{A}\right) = (17\times10^{-19})\frac{0.3}{3.14\ \times\ (0.9\times10^{-3})^2} = 0.008\Omega$$
   (b) $P = \frac{V^2}{R} = \frac{V^2A}{\rho\, L} = \frac{1.428\times10^{-6}}{510\times10^{-9}} = 2.8\, watt$

2. Which part suffer from a greater stress:
   (a) A rectangular aluminium bar of 24.6 mm x 30.7 mm cross section under a load of 7640 kg and, therefore, a force of 75,000N.
   (b) A round steel bar that has a diameter of 12.8 mm under a 5000 kg load.

   Solution:

   Stress is the force per unit area. Also *f*= *ma* with *a*=9.8m/s^2

   Units=Newton/(m*m)=Pascal.

   Calculations:

   (a)
   $$s = \frac{(7640)(9.8)}{(0.0246)(0.0307)} = 100\ MPa$$
   (b)
   $$s = \frac{(5000)(9.8)}{(\frac{\pi}{4})(0.0128)^2} = 380\ MPa$$

   Extra examples

3. A 50 mm gage length is placed on a copper rod. The rod is strained so that the gage marks are 59 mm apart. Calculate the strain.
4. If the average modulus of elasticity of the steel used is 205,000 MPa. How much will a wire 2.5 mm in diameter and 3 meters long be extended when it supports a load of 500 kg?
5. A wire of magnesium alloy is 1.05 mm in diameter. Its modulus of elasticity is 45,000 MPa. Plastic deformation starts with a load of 10.5 kg. The total strain is 0.0081 after loading to 12.1 kg. How much permanent strain has occurred with a load of 12.1 kg.
6. What is the elastic strain in a copper rod when a stress of 70 MPa applied on it? Note that its modulus of elasticity is 110,000 MPa.
7. A rod of copper should not be stressed more than 70 MPa in tension. What diameter is required if it is to carry a load of 2000 kg?
8. Copper has a resistivity of 17×10^{-19} Ω.cm.
   (a) What is the end-to-end resistance of a copper strip of 2 cm long, 5 mm wide and 1 mm thick?
   (b) Calculate the conductivity of this copper.