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Material science and engineering

Second year

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CHAPTER ONE

Classification of Materials

1-1 Classification of engineering materials

a-Metals and Alloys

Metals are inorganic materials that are normally combination of metallic elements.
- They usually have a crystalline structure and are good thermal and electrical conductivity.
- Many metals have high strength and high elastic module.
- They also have sufficient ductility, which is important for many engineering applications.
- They are least resistance to corrosion.
- An alloy is a mixture of two or more elements in solid solution in which the major component is a metal. Combining different ratios of metals as alloys modify the properties of pure metals to produce desirable characteristics. The aim of making alloys is generally to make them less brittle, harder, and resistant to corrosion. Examples of alloys are steel (iron and carbon), brass (copper and zinc), and bronze (copper and tin).

b-Ceramics and glasses

They are inorganic materials consisting of both metallic and non-metallic elements bonded together chemically.
- They can be crystalline (ceramics), non-crystalline (glasses) or mixture of both (glass-ceramics).
- They are good electrical and thermal insulators.
- They have high hardness, high moduli, and high temperature strength.
- They are resistant to high temperature and corrosive environments.
- They are very brittle.

c-Polymers

They are organic materials which consist of long molecular chain and they are chemically based on carbon and hydrogen.
Most polymers are non-crystalline, but some consist of mixtures of both crystalline and non-crystalline regions.

- They are generally have low density and are not stable at high temperatures.
- They generally have a good strength to weight ratio.
- Most of them are corrosion resistant, but cannot be used at high temperatures.
- They provide a good electrical and thermal insulation.
- Polymers may be either ductile (thermoplastic) or brittle (thermosetting).

d-Semiconductors
They have electrical properties intermediate between metallic conductors and ceramic insulators.
- Silicon is the most commercially important semiconductors.
- Semiconductors may be elemental materials such as silicon and germanium, or alloys such as silicon germanium.
- The semiconductor devices are combined with simpler components, such as semiconductor capacitors and resistors, to produce a variety of electronic devices.

e-Composite materials
Materials where two or more of the above materials are brought together. They are designed to combine the best properties of each of its components.
- Usually they consist of a matrix and a reinforcement.
- Fiber, a combination of glass and a polymer, is an example. Concrete is other familiar composites.

1-2 Classification of materials based on structure

a-Crystalline materials
- single crystals
- polycrystalline

b-Amorphous materials

1-3 Classification of materials based on the function

a-Mechanical material  b-Electronic material  c-Magnetic material  d-Optical material  e-Medical material

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CHAPTER TWO

Mechanical Properties of Materials

2-1 Stress

It is a measure of force acting on the unit area over which the force is applied.

\[ \sigma = \frac{F}{A_0} \]

Where \( F \): force (N)
\( A_0 \): original area (m²)
\( \sigma \): stress (N/m²)

There are tensile, compressive, shear, and bending stresses illustrated in fig(2-1).

\[ \varepsilon = \frac{\Delta l}{l_0} \]

Where \( \varepsilon \): strain, \( \Delta l \): change in length, \( l_0 \): original length.

-Strain is expressed as a fraction (or percent).

-Strain may be elastic or plastic as shown in fig (2-2).

1- Elastic Strain

It is reversible, that is, when the stress is removed, the strain disappears. Elastic strain is commonly a linear function of stress obeying Hooke's law of physics.
2-3-1 Some Concepts Developed From The Stress-Strain Diagram

1-The elastic limit: it is the critical stress value needed to initiate plastic deformation.

2-yield point: at which there is an appreciable elongation or yielding of the material without any corresponding increase of load; indeed, the load may actually decrease while the yielding occurs. However, the phenomenon of yielding is peculiar to some materials and other material do not possess this point as shown in fig (2-4).

3-yield strength: closely associated with yield point. For materials which do not have a well defined yield point, yield strength is determined by the offset method. This consists of drawing a line, parallel to the linear portion of the stress-strain curve, this line being started at some specified strain offset, usually 0.002. As shown in fig (2-5), the intersection of this line with the stress-strain curve is called the yield strength. The magnitude of the yield strength for the a metal is a measure of its resistance to plastic deformation.

4-ultimate or tensile strength: it is the maximum tensile stress a material can withstand before failure. It is a feature of the engineering stress-strain curve and cannot be found in the true stress-strain curve. However, at this maximum stress, a small contraction or neck begins to form at some points, all subsequent deformation is confined at this neck fig (2-6).

5-rupture or fracture strength (engineering breaking strength): it is the stress at fracture, it is computed by dividing the fracture load by the original cross-sectional area, so its some what lower than tensile strength.

6-actual rupture strength or true fracture strength: it is the true stress at fracture which is defined as the load divided by the instantaneous cross-sectional area ($A_i$) over which deformation is occurring (i.e., the neck, past the tensile point). The true stress-strain curve is compared with the stress-strain curve in fig (2-3). It can be seen that the true stress continues to increase after necking because, although the load required decreases, the area decreases even more.

$$\sigma_f = \frac{F}{A_i} \quad \text{where} \quad \sigma_f = \text{True fracture strength}.$$  

$$\varepsilon_f = \ln \frac{l}{l_0} = \ln \frac{A_0}{A_i} \quad \text{where} \quad \varepsilon_f = \text{True fracture strain}.$$  

If no volume change occurs during deformation, that is, if $A_0 = A_i$, then:

$$\sigma_f = \frac{F}{A_i} = \frac{lF}{A_0} \quad \text{so} \quad \varepsilon_f = \ln \frac{l}{l_0} = \sigma \left[ \frac{l_0 + \Delta l}{l_0} \right] = \sigma (1 + \varepsilon)$$

and

$$\varepsilon_f = \ln \frac{l}{l_0} = \ln \left[ \frac{l_0 + \Delta}{l_0} \right] = \ln (1 + \varepsilon)$$

The above equations are valid only to the onset of necking.
2-Plastic Strain

It is a permanent deformation in a material. In this case, when the stress is removed, the material does not go back to its original shape.

![Elastic Strain and Plastic Strain Diagram](image)

Elastic Strain                          Plastic Strain

Fig (2-2)

2-3 Stress-Strain Diagram

For most metals that are stressed in tension and at relatively low levels, a plot of stress versus strain results in a linear relationship, as shown in fig (2-3). Stress and strain are proportional to each other through the relationship: \[ \sigma = E \varepsilon \]

This is known as Hook’s law, and the constant of proportionality \( E \) is the modulus of elasticity, or Young’s modulus.

The slope of the linear segment corresponds to the modulus of elasticity.

The modulus of elasticity is:

a. A measure of stiffness, the greater the modulus, the stiffer the material.

b. A material’s resistance to elastic deformation, the greater the modulus, the smaller the elastic strain.

c. A measure of the resistance to separation of adjacent atoms, that is, the interatomic bonding forces. So:

\[ E_{\text{ceramic}} > E_{\text{metal}} = E_{\text{polymer}} \]

The proportionality of stress to strain ends at the proportional limit, which is defined as the level of stress above which the relationship between stress and strain is not linear. Deformation in which stress and strain are proportional is called elastic deformation.
Fig. 2.3 — Stress-strain diagram.

Fig. 2.4 — Comparative stress-strain diagrams for different materials.

Fig. 2.5 — Yield strength determined by offset method.
Figure 2.6 Typical engineering stress–strain behavior to fracture, point F. The tensile strength $TS$ is indicated at point $M$. The circular insets represent the geometry of the deformed specimen at various points along the curve.
2-4 **Ductility** :- It is a measure of the total plastic strain that accompanies fracture.

Ductility may be expressed as: 
\[ \epsilon_r \]

1. Elongation which is commonly expressed as percent.
   \[ \text{EL\%} = \frac{(l_f-l_0)}{l_0} \times 100\% \]

2. Reduction in area (R of A) at the point of fracture:
   \[ R \text{ of } A = \frac{(A_0-A_f)}{A_0} \]

A highly ductile material has high values of EL and R of A.

2-5 **Brittle material** :- It is the material that experiences very little or no plastic deformation upon fracture. In more brittle materials, failure occurs at the maximum load where tensile strength and breaking strength are the same. Fig(2-7)

![Stress-Strain Diagram](image)

**Figure 2-7.** The stress-strain behavior of brittle materials compared with that of more ductile materials.

2-6 **The Tensile Test: Use Of The Stress-Strain Diagram**

The tensile test is popular since the properties obtained could be applied to design different components. The tensile test measures the resistance of a material to a static or slowly applied force. A test setup is shown in figure (2-8), in which the specimen is placed in the testing machine and a force F, called the load, is applied. A universal testing machine on which tensile and compressive tests can be performed is used. A strain gage is used to measure the amount that the specimen stretches between the gage marks when the force is applied. Thus, what is measured is the change in length of the specimen (\(\Delta l\)) over a particular original length (\(l_0\)). Information concerning the strength, young’s modulus, and ductility of a material can be obtained from such a tensile test. Typically, a tensile test is conducted on metals, alloys, and plastics. Tensile tests can be used for ceramics, however, these are not popular because the sample may fracture while it is being aligned.
2-7 Toughness

It is also known as work of fracture. It is a measure of the ability of a material to absorb energy up to fracture. It is usually measured by the energy absorbed in a notch impact test (fig. 2-9), but the area under the tensile stress-strain up to the point of fracture is also a measure. Ductile materials are tougher than brittle ones, fig. (2-10).
2-8 The Bend Test For Brittle Materials

In many brittle materials, the normal tensile test cannot easily be formed because just placing a brittle material in the grips of the tensile testing machine causes cracking. These materials may be tested using the bend test [fig(2-11)]. By applying the load at three points and causing bending, the flexural strength or modulus of rupture, describes the material's strength:

\[
\text{Flexural strength} = \frac{F}{b.d}
\]

The results of the bend test are similar to the stress-strain curves, however, the stress is plotted versus deflection rather than versus strain[fig(2-12)]. The modulus of elasticity in bending, or the flexural modulus (\(E_{\text{bend}}\)), is calculated in the elastic region of figure (2-12).

Flexural modulus = \(E_{\text{bend}} = \frac{F}{b.d}\)

\(\delta\) is the deflection of the beam when a force \(F\) is applied

![Diagram](image)

Figure 2-11 (a) The three-point bend test often used for measuring the strength of brittle materials, and (b) the deflection \(\delta\) obtained by bending.

![Stress-deflection curve](image)

Figure 2-12. Stress-deflection curve for MgO obtained from a bend test.

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2-9 Poisson’s ratio ($\mu$)

It relates the longitudinal elastic deformation produced by a simple tensile or compressive stress to the lateral deformation that occurs simultaneously.

$$\mu = -\epsilon_{\text{lateral}}/\epsilon_{\text{longitudinal}}$$

$\mu$ is always positive since $\epsilon_x$ and $\epsilon_y$ will always be of opposite sign.

For many metals in the elastic region, the poisson’s ratio is typically about 0.3.

2-10 Modulus of resilience ($E_r$)

It is the elastic energy that a material absorbs during loading and subsequently releases when the load is removed. And it is the area contained under the elastic portion of a stress-strain curve as shown in fig(2-13).

$$E_r = \int \sigma \, d\varepsilon$$ in which $\varepsilon_y$ is the strain at yielding.

For linear elastic behavior:

$$E_r =$$

Thus, resilient materials are

![Figure 2-13 Schematic representation showing how modulus of resilience (corresponding to the shaded area) is determined from the tensile stress-strain behavior of a material.](image)

2-11 Hardness

It is a measure of the resistance to penetration of the surface of a material by hard object. It is often measured by pressing

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A pointed diamond or hardened steel ball is introduced into the surface of the material. The hardness is generally defined as the indentor force divided by the projected area of the indent. Hardness is measured by different hardness techniques: Brinell, Vickers, Rokwell, and Knoop tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>Indenter</th>
<th>Shape of Indentation</th>
<th>Load</th>
<th>Formula for Hardness Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brinell</td>
<td>10-mm sphere of steel or tungsten carbide</td>
<td></td>
<td>$P$</td>
<td>$HB = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})}$</td>
</tr>
<tr>
<td>Vickers microhardness</td>
<td>Diamond pyramid</td>
<td></td>
<td>$P$</td>
<td>$HV = 1.854P/d_1^2$</td>
</tr>
<tr>
<td>Knoop microhardness</td>
<td>Diamond pyramid</td>
<td></td>
<td>$P$</td>
<td>$HK = 14.2P/P$</td>
</tr>
<tr>
<td>Rockwell and Superficial</td>
<td>Diamond cone, 1/4 in. diameter steel spheres</td>
<td></td>
<td>$60 , kg$</td>
<td>Rockwell</td>
</tr>
<tr>
<td>Rockwell</td>
<td></td>
<td></td>
<td>$100 , kg$</td>
<td>Rokwell</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$150 , kg$</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>$15 , kg$</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>$30 , kg$</td>
<td>Superficial Rokwell</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$45 , kg$</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2-1** Hardness Testing Techniques

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Chapter Three
Atomic Structure

3-1 The structure of atom

Properties of solid materials are a function of geometrical atomic arrangement and interaction between constituent atoms or molecules.

- The Atom: Nuclens (neutrons, protons), Electrons.
  - Electron, proton are electrically charged.
    (magnitude of $1.6 \times 10^{-19}$ C).
  - Neutron: electrically neutral.

- Atomic Mass Unit: used for computations of atomic weight. $1$ AMU = $1/12$ of the atomic mass of the most common isotope of carbon, Carbon $12$, $^{12}$C.

3-2 Atomic Bonding

There are four important mechanisms by which atoms are bonded in engineered materials. These are:

3-2-1 primary Bonds

a. Ionic Bond

Ionic bonding occurs between charged particles. It occurs between metal atoms and nonmetal atoms. Metals usually have 1, 2, or 3 electrons in their outer shell.
Non metals have 5, 6, or 7 electrons in their outer shell.

The atoms that gain electrons called anions.
- The atoms that lose electrons called cations.
- An example of an ionic bond is the attraction between sodium and chloride ions.
- Generally, solid materials with ionic bonds:
  1. are hard because particles cannot easily slide past one another.
  2. are good insulators because there are no free electrons or ions (unless dissolved or melted).
  3. are brittle and tend to cleave rather than deform because bonds are strong.
  4. have high melting point because ionic bonds are relatively strong.

Fig (3-1) show the ionic bond for NaCl.

b - Covalent Bond

Where a compound only contains nonmetal atoms, a covalent bond is formed by atoms sharing two or more electrons.

Nonmetals have 4 or more electrons in their outer shells. With this many electrons in the outer shell, it would require more energy to remove the electrons than would be gained by making new bonds. Therefore, both the atoms involved share a pair of electrons.

The atoms can be of the same element or different elements.

The bonds between the atoms are strong but the bonds between molecules are usually weak. This makes many solid materials with covalent bonds brittle.
Many ceramic materials have covalent bonds.
- Some common features of materials with covalent bond are:
  1) hard, 2) Fig (3-2) show covalent bonds.

**c. Metallic Bond**

Metallic elements are contain only one to three valence electrons (i.e., electrons in the outer shell). The bond between these electrons and the nucleus is relatively weak.
- Aluminum atoms, for example, are grouped together in a block of metal; the outer electrons leave individual atoms to become part of common "electron cloud". Since the aluminum atoms lose two electrons, they end up having a positive charge and are designated Al ions (cations). These ions repel each other but are held together in the block because the negative electrons are attracted to the positively charged ions. A result of sharing of electrons is the cations arrange themselves in a regular pattern. This regular pattern of atoms is the crystalline structure of metals, Fig (3-3).
- Some common features of materials with metallic bonds are:
  1) exhibit relatively high Young's modulus since the bonds are strong.
3.2.2 Secondary Bonds (Van der Waals Bond)

The Van der Waals bond are particularly important in plastics and polymers. These materials are made up of long string molecules consisting of carbon atoms covalently bonded with other atoms, such as hydrogen, nitrogen, oxygen, and fluorine. The covalent bonds within the molecules are very strong and rupture only under extreme conditions. The bonds between the molecules that allow sliding and rupture to occur are called Van der Waals forces.

As molecules in plastics become larger, the Van der Waals forces between molecules also increase. For example, in polyethylene, the molecules are composed of hydrogen and carbon atoms in the same ratio as ethylene gas. But there are more of each type of atom in the polyethylene molecules and as the number of atoms in a molecule increases, the matter passes from gas to liquid and finally to a solid.

When ionic and covalent bonds are present, there is some imbalance in the electrical charge of the molecule. Take water as an example. The hydrogen atoms are bonded to the oxygen atom at an angle of 104.5°. This angle produces a positive polarity at the hydrogen-rich end of the molecule and a negative polarity at the other end. A result of this charge imbalance is that water molecules are attracted to each other. This is the force that holds
the molecules together in a drop of Water. Fig. 1.4.

- Polyurethane materials which can be easily remelted for forming or recycling. It consists of long chain-like molecules. Heat can be used to break the van der Waals forces between the molecules and change the form of the material from a solid to a liquid.

b. Thermosetting materials which cannot be easily remelted because it has a three-dimensional network of covalent bonds. These bonds cannot be easily broken by heating or, therefore, can not be remelted and formed as easily as thermoplastic.
3-3 Interatomic spacing

There are attractive forces that pull atoms together into solids (and liquids). But the center of ions cannot be brought even closer together into a still more stable, lower-energy position because of the repulsion of the electrons of the adjacent atoms at close distances. So the space between atoms is caused by interatomic repulsive forces, which exist in addition to the interatomic attractive forces. The equilibrium distance is the distance at which the repulsive and the attractive forces are equal.

In a solid metal, the equilibrium distance is approximately equal to the atomic diameter or twice the atomic radius but for ionically bonded materials, the spacing is the sum of the two different ionic radii.

3-4 Atomic and ionic radii

- The radii of atoms and ions are different because ions will either gained or lost electrons.
- A negative ion is larger than its corresponding atom. The added electrons are not as closely attracted to the nucleus as were the original electrons. For example: radius of an oxygen atom is 0.6\text{Å}.
radius of an oxygen anion is 1.32 Å.
- Anions are larger than cations.

3.5 Bonding Forces and Energies

The ionic bond will be used to illustrate the balance between attractive and repulsive forces in materials. The Coulombic force $F_c$ developed between two point charges is related to as follows:

$$F_c = -\frac{1}{\varepsilon_0} \frac{(Z_1 q_1)(Z_2 q_2)}{a^2}$$

$\varepsilon_0$ is the inherent ionic distance (m).
$Z_1$ and $Z_2$ are the charges of the two ions, and may be either positive or negative.
$q_1$ is the electronic charge of $1.6 \times 10^{-19}$ C.
$\varepsilon_0$ is the proportionality constant, depends on the units used when considering adjacent ions $= 9 \times 10^9 \text{ Nm}^2 / \text{C}^2$.
$F_c$ - Coulombic force $(\text{J} / \text{m})$.
Electron repulsion force $F_r$ becomes significant as atoms approach one another.

$$F_r = -\frac{bn}{a^{n+1}} \quad 6 < n < 12$$

$b$ - repulsion coefficient $\mu \text{m}^9$ (empirical constant).
$n$ - is an empirical constant $= 9$ for ionic solids.
Since \( E = \int (F_c + F_R) \, da = \text{net energy} \)

\[
E = \int \left[ -\frac{k_0 z_1 z_2 q^2}{a^2} - \frac{\mu b}{a^{n+1}} \right] \, da = \frac{k_0 z_1 z_2 q^2}{a} + \frac{b}{a^n}
\]

\[ E = E_c + E_R \]

- like charges ions require energy as they approach each other \( (E_c > 0) \)
- unlike charges ions release energy as they approach each other \( (E_c < 0) \)

3.6 Bonding energy

At equilibrium, \( a = \sigma_0 \), \( F = 0 = \frac{dE}{da} \)

\( E_0 \) - the energy required to break the bond (bonding energy). Fig (3-5)

- number of material's properties depend on \( E_0 \)
- material having large \( E_0 \) also have high melting temperature; at room temperature solid substances are formed for large \( E_0 \) whereas for small energies the gasesous state is favored
- higher bonding energy \( \rightarrow \) higher melting point \( \rightarrow \) higher modulus of elasticity (great force is required to stretch the bond)
- High bonding energy \( \Rightarrow \) low coefficient of thermal expansion (maintain their dimension more closely when the temperature changes).

* Coefficient of thermal expansion: means how much a material expands or contracts when its temperature is changed.
Fig (3-3)

Fig (3-4)
Figure 25 (a) The separation for two isolated atoms, and net potential energy. The dependence of repulsive and attractive forces on interatomic separation.
Chapter Four

Atomic order in Solid

Arrangements of atoms or ions play an important role in determining the microstructure and properties of a material.

1. Types of atomic or ionic arrangements (Fig 7.1)

1. No order: In monoatomic gases, such as argon (Ar), atoms or ions have no orderly arrangement. These materials randomly fill up whatever space is available to them.

2. Short-range order (SRO): A material displays (SRO) if the special arrangement of the atoms extends only to the atom's nearest neighbors. Each water molecule in steam has a short-range order due to the covalent bonds between the hydrogen atoms and oxygen atoms. However, the water molecules in steam have no special arrangement with respect to each other's position. A similar situation exists in materials known as inorganic glasses. The tetrahedral structure in silica that four oxygen ions be bonded to each silicon ion. In glassy, individual tetrahedral units are joined together in a random manner, so there is no periodicity in their arrangement. In contrast, in quartz and other forms of
crystalline silicon. The Si four tetrahedra are indeed connected in different periodic arrangements.

3- Long-Range order (LRO): Most metals and alloys, semiconductors, ceramics, and some polymers have a crystalline structure in which the atoms or ions display LRO (periodic array) at special atomic arrangements extending over much larger length scales > 100 nm.

4- Liquid crystals (LCs): Are polymeric materials that have a special type of order. It behaves as amorphous materials (liquid-like) in one state. However, when an external stimulus (such as an electric field or temperature change) is provided, some polymer molecules undergo alignment and form small regions that are crystalline, hence the name "liquid crystals".

4.2 Classification of solid materials

Solid materials may be classified according to the regularity with which atoms or ions are arranged with respect to one another.

1. Amorphous material (non-crystalline materials)
It is any material that exhibits only a short-range order of atoms or ions. Glasses, which typically form in ceramic and polymer systems are good examples of amorphous materials. The atoms in amorphous material have no periodic packing; it occurs for complex structures and rapid cooling. Many amorphous materials can be crystallized in a controlled fashion; example of amorphous material are silicate glasses, metallic glasses and many polymers.

2. Crystalline materials: Including metals and many ceramics, have both short and long range order. The long-range periodicity in these materials is described by the crystal structure. Atoms in crystalline solid are positioned in an orderly and repeated pattern that is in contrast to the random and disordered atomic distribution found in non-crystalline or amorphous materials.

3. Crystal Structure

Crystal structure pertains to the arrangement of atoms in the crystalline solid material
a. Lattice

is a collection of points, called lattice points, which are arranged in a periodic pattern so that the surroundings of each point in the lattice are identical. The concept of lattice describes the arrangements of atoms or ions. A group of one or more atoms, located in a particular way with respect to each other and associated with each lattice point, is known as the basis. Crystal structure = lattice + base.

b. Unit Cell

It is the subdivision of a lattice that still retains the overall characteristics of the entire lattice. By stacking identical unit cells, the entire lattice can be constructed.

4.4 Characteristics of a Crystal Structure

1. Lattice parameters: They describe the size and shape of the unit cell.

2. Number of lattice points: A lattice point at a corner of one unit cell is shared by seven adjacent unit cells.

3. Number of atoms per unit cell: It is
equal to the product of the number of atoms per lattice point and the number of lattice points per unit cell.

4. Atomic packing factor: is the fraction of space occupied by atoms.

5. Coordination number (CN): It is the number of atoms touching a particular atom, or the number of nearest neighbors for that particular atom.

The factors control the coordination number of an atom:
- The covalency.
- The ionic radii.

6. Close-packed direction: It is the direction in the unit cell along which atoms are in continuous contact.

4.5 Metallic crystal structure

1. Simple cubic unit cell (SC)
2. Body centered cubic unit cell (BCC)
3. Face centered cubic unit cell (FCC)
4. Hexagonal close-packed unit cell (HCP).
### Table 1
Coordinations Numbers and Geometries for Various Coordination-Atom Ratios

<table>
<thead>
<tr>
<th>Coordination Number</th>
<th>Coordination Atom Ratios</th>
<th>Coordination Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>&lt;0.155</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.155 - 0.225</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.225 - 0.414</td>
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</tr>
<tr>
<td>6</td>
<td>0.414 - 0.732</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.732 - 1.0</td>
<td></td>
</tr>
</tbody>
</table>


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**Figure 1**

Levels of atomic arrangements in materials:
- (a) Metastable glasses have short-range order.
- (b) Metal-covalent glasses have no regular ordering of the material.
- (c) Polymers and some ceramics have regular ordering extending through the material.
- (d) Crystalline solids have long-range order.
- (e) Polymers and some ceramics have regular ordering extending through the material.
Figure 7.3 For the hexagonal close-packed crystal structure, (a) a reduced-sphere unit cell (a and c represent the short and long edge lengths, respectively), and (b) an aggregate of many atoms. (Figure (b) from W. G. Moffatt, G. W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 51. Copyright © 1964 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)