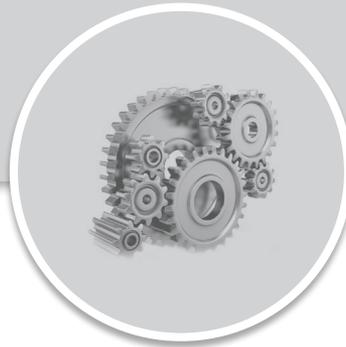


# MECHANICAL ENGINEERING

## Material Science



Comprehensive Theory  
*with Solved Examples and Practice Questions*





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## **Material Science**

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# Introduction to Engineering Materials

CHAPTER

1

## 1.1 INTRODUCTION

Why do we study materials?

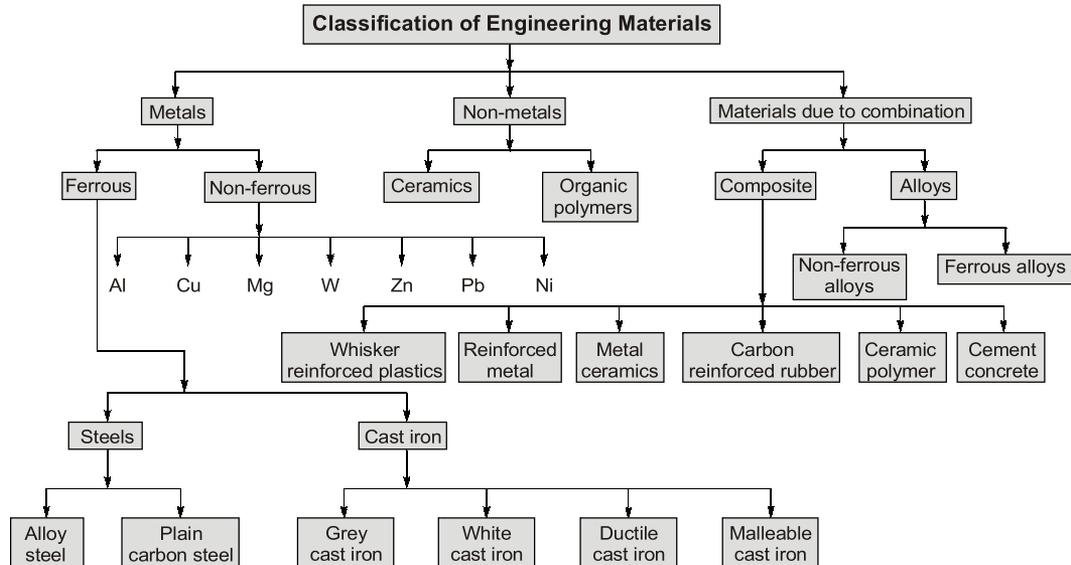
Many times an applied scientist or engineer, whether mechanical, civil, chemical, or electrical, is at one time or another exposed to a design problem involving materials, such as a transmission gear, the superstructure for a building, an oil refinery component, or an integrated circuit chip. Of course, materials scientists and engineers are specialists who are totally involved in the investigation and design of materials.

Many times, a materials problem is one of selecting the right material from the thousands available. The final decision is normally based on several criteria. First of all, the **in-service conditions** must be characterized, for these dictate the properties required of the material. On only rare occasions does a material possess the maximum or ideal combination of properties. Thus, it may be necessary to trade one characteristic for another. The classic example involves strength and ductility; normally, a material having a high strength has only a limited ductility. In such cases, a reasonable compromise between two or more properties may be necessary. A second selection consideration is any **deterioration of material properties** that may occur during service operation. For example, significant reductions in mechanical strength may result from exposure to elevated temperatures or corrosive environments.

Finally, probably the overriding consideration is that of economics: What will the finished product cost? A material may be found that has the ideal set of properties but is prohibitively expensive. Here again, some compromise is needed. The cost of a finished piece also includes any expense incurred during fabrication to produce the desired shape. The more familiar an engineer or scientist is with the various characteristics and structure property relationships, as well as the processing techniques of materials, the more proficient and confident he or she will be in making judicious materials choices based on these criteria.

## 1.2 MATERIAL CLASSIFICATION

Most engineering materials may be classed into one of the following types:



### 1.2.1 Metals

Metals are the ones which have **free electrons**. They are capable of changing shape upon machining and gives good finish. At room temperature they are usually solid (except mercury) and to some extent they are malleable and ductile. Atoms in metals and their alloys are arranged in a very orderly manner and relatively dense in comparison to ceramics and polymers. Metals are good conductors of heat and electricity. Example Copper, Silver and Gold etc.

#### General Characteristics of Metals

- Luster
- Plastic deformability/Formability
- Relatively high melting point
- Malleability
- Rigidity
- Good thermal and electrical conductivity
- Hardness
- Castability
- Strength
- Opaque
- Machinability
- Low specific heat
- Ductility
- Stiffness
- Dimensional stability.
- Weldability

#### Examples of commonly employed metals are :

Iron, Aluminium, Copper, Zinc, Magnesium, etc.

### 1.2.2 Ceramic Materials

- Ceramics usually consist of oxides, nitrides, carbides, silicates of various metals.
- Ceramics are any inorganic, non-metallic solids (or super-cooled liquids) processed or used at high temperatures.
- Ceramic materials are rock or clay mineral materials.
- Ceramic materials contain compounds of metallic and non-metallic elements, such as  $MgO$ ,  $SiO_2$ ,  $SiC$ ,  $BaTiO_3$ , glass, etc. Such compounds contain both ionic and covalent bonds.
- In addition, they are typically very hard. Historically, ceramics have exhibited extreme brittleness (lack of ductility) and are high susceptibility to fracture. However, newer ceramics are being engineered to have improved resistance to fracture.

## 1.4 TYPES OF BOND

Solid state exhibits a crystal structure which is having a definite geometry except amorphous state like glass. Various types of bonding in crystal structure:

1. **Ionic Bond** : Strong electrostatic attraction between cations and anions is called ionic bond. These bonds are permanent and atoms drift throughout the lattice structure.
2. **Covalent Bond** : In this type of bond there is a sharing of one or more electrons from the adjacent atoms.
3. **Metallic Bond** : Metallic bond is formed when material (metal) have one, two or three valence electrons. These electrons are not bound to any particular atom in the solid and drift through out the entire metal.
4. **Vander Waals Bond** : In this bond, these are attractive forces that hold molecules close together. These attractive forces are more commonly referred to as intermolecular forces. The bond formation generally takes place in neutral atoms like inert gases.



### OBJECTIVE BRAIN TEASERS

**Q.1** Which of the following methods of synthesis of nanomaterials has solid as starting phase?

- |                       |                   |
|-----------------------|-------------------|
| 1. Electro deposition | 2. Sliding wear   |
| 3. Spark erosion      | 4. Ball milling   |
| (a) 1, 2 and 3        | (b) 1, 2, 3 and 4 |
| (c) 1, 3 and 4        | (d) 2, 3 and 4    |

**Q.2** Two important properties of nano substances are

- (a) Pressure and friction
- (b) Temperature and friction
- (c) Sticking and temperature
- (d) Sticking and friction

**Q.3** Match **List-I** (Materials) with **List-II** (Application) and select the correct answer using the codes given below the lists:

**List-I**

- A. Fibre reinforced plastics
- B. Acrylics
- C. Phenolics
- D. Butadiene rubber

**List-II**

1. Automobile tyre
2. Aircraft
3. Lenses
4. Electric switch cover

**Codes:**

	A	B	C	D
(a)	1	4	3	2
(b)	2	3	4	1
(c)	1	3	4	2
(d)	2	4	3	1

**Q.4** Nano composite materials are highly preferable in design consideration for their

- (a) High resistance to crack propagation
- (b) Vibration resistance
- (c) Impact resistance
- (d) High resilience

**Q.5** **Statement (I):** A short specimen elongates proportionally more during the same time period than does a long specimen.

**Statement (II):** The strain rate is a function of the specimen length.

- (a) Both Statement (I) and Statement (II) are individually true and Statement (II) is the correct explanation of Statement (I).
- (b) Both Statement (I) and Statement (II) are individually true but Statement (II) is NOT the correct explanation of Statement (I).
- (c) Statement (I) is true but Statement (II) is false.
- (d) Statement (I) is false but Statement (II) is true.



### ANSWER KEY

1. (d)    2. (d)    3. (b)    4. (b)    5. (a)

## HINTS &amp; EXPLANATIONS

1. (d)  
Electro deposition has liquid as its starting phase, while rest three have solid as starting phase.
2. (d)  
For Nano substances both sticking and friction are considerable properties.

3. (b)

Materials	Their application
Acrylics	Lenses, drafting equipment
Phenolics	Motor housing, electrical fixtures
Butadiene rubber	Automobile tyres
Fibre reinforced plastic	Aircraft

5. (a)

Shorter the specimen, more the strain rate if subjected to same deformation in a given time. Illustrated below is two rubber bands, one of 20 mm and the other of 100 mm gauge length. Both are elongated by 10 mm within a period of 1 sec. The strains rates are  $0.5 \text{ s}^{-1}$  and  $0.1 \text{ s}^{-1}$  respectively, which implies short band being subjected to a strain rate five times as high as that for the long band, although both are being stretched at the same deformation rate.



## CONVENTIONAL BRAIN TEASERS

Q.1 Define nano materials. How are they classified? What are the different types of method used to manufacture nano-materials? Explain briefly arc discharge method.

Solution:

**Nano-materials** : The materials which have at least one external dimension or any internal structure (like grain size or any separated small structures in materials) is less than 100 nm are called nanomaterials. In other words, these are those materials which contain an internal morphology less than 100 nm. The internal morphology may be in the form of sphere, clusters, fibres, tubes, etc.

**Nanomaterials are classified according to the internal morphology, as**

- (i) Zero dimensional (spheres, clusters).
- (ii) One dimensional (tubes, fibres and rods).
- (iii) Two dimensional (films).
- (iv) Three dimensional (particles).

**Methods used to manufacture nano-materials :**

- (i) Top-down approach (bulk material to nanomaterial).
- (ii) Bottom to top approach (atoms to nanomaterial).

**Arc discharge method** : It is used to make carbon nano tubes (CNT).

Q.2 Briefly explain the following methods to produce nano-materials

- (i) Mechanical grinding
- (ii) Laser ablation

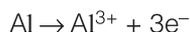
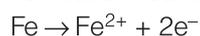
## 10.1 INTRODUCTION

To one degree or another, most materials experience some type of interaction with a large number of diverse environments. Often such interactions impair a material's usefulness as a result of the deterioration of its mechanical properties (e.g., ductility and strength), other physical properties, or appearance. Deteriorative mechanisms are different for the three material types. In metals, there is actual material loss either by dissolution (corrosion) or by the formation of nonmetallic scale or film (oxidation).

Corrosion is defined as the destructive and unintentional attack of a metal; it is electrochemical and ordinarily begins at the surface. Corrosion is the deterioration of a material as a result of its interaction with its surroundings which converts refined metal to their more stable oxide. The problem of metallic corrosion is one of significant proportions. The consequences of corrosion are all too common. Familiar examples include the rusting of automotive body panels and radiator and exhaust components.

## 10.2 ELECTROCHEMICAL CONSIDERATIONS

For metallic materials, the corrosion process is normally electrochemical, that is, a chemical reaction in which there is transfer of electrons from one chemical species to another. Metal atoms characteristically lose or give up electrons in what is called an oxidation reaction. Examples in which metal oxidizes are,

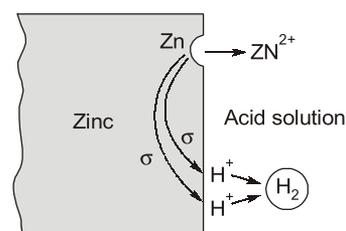


The site at which oxidation takes place is called the anode; oxidation is sometimes called an anodic reaction. The electrons generated from each metal atom that is oxidized must be transferred to and become a part of another chemical species in what is termed a reduction reaction. For example, some metals undergo corrosion in acid solutions, which have a high concentration of hydrogen ( $\text{H}^{+}$ ) ions; the  $\text{H}^{+}$  ions are reduced as follows:



and hydrogen gas ( $\text{H}_2$ ) is evolved.

The location at which reduction occurs is called the cathode. Furthermore, it is possible for two or more of the preceding reduction reactions to occur simultaneously. An overall electrochemical reaction must consist of at least one oxidation and one reduction reaction, and will be the sum of them; often the individual oxidation and reduction reactions are termed half-reactions. There can be no net electrical charge accumulation from the electrons and ions; the total rate of oxidation must equal the total rate of reduction, or all electrons generated through oxidation must be consumed by reduction.

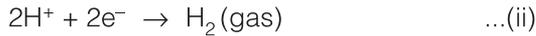


**Fig. :** The electrochemical reactions associated with the corrosion of zinc in an acid solution.

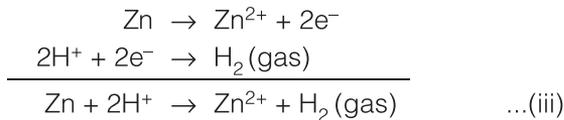
For example, consider zinc metal immersed in an acid solution containing H<sup>+</sup> ions. At some regions on the metal surface, zinc will experience oxidation or corrosion as illustrated in figure below and according to the reaction,



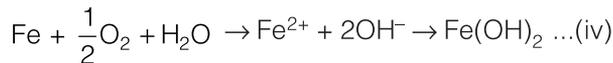
Because zinc is a metal, and therefore a good electrical conductor, these electrons may be transferred to an adjacent region at which the H<sup>+</sup> ions are reduced according to



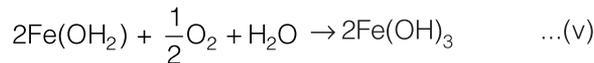
If no other oxidation or reduction reactions occur, the total electrochemical reaction is just the sum of reactions (i) and (ii).



Another example is the oxidation or rusting of iron in water, which contains dissolved oxygen. This process occurs in two steps; in the first, Fe is oxidized to Fe<sup>2+</sup>

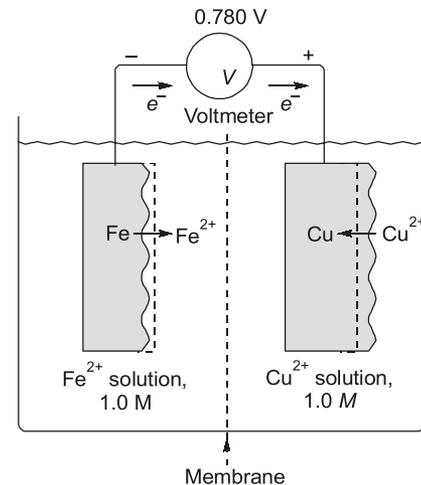


and, in the second stage, to Fe<sup>3+</sup> [as Fe(OH)<sub>3</sub>] according to



The compound Fe(OH)<sub>3</sub> is the all-too-familiar rust.

As a consequence of oxidation, the metal ions may either go into the corroding solution as ions (reaction (i)), or they may form an insoluble compound with non-metallic elements as in reaction (v).



**Fig. :** An electrochemical cell consisting of iron and copper electrodes, each of which is immersed in a M solution of its ion. Iron corrodes while copper electrodeposits.

### 10.3 THE GALVANIC SERIES

The Galvanic series represents the relative reactivities of a number of metals and commercial alloys in seawater. The alloys near the top are cathodic and unreactive, whereas those at the bottom are most anodic; no voltages are provided. Comparison of the standard emf and the galvanic series reveals a high degree of correspondence between the relative positions of the pure base metals.

Most metals and alloys are subjected to oxidation or corrosion to one degree or another in a wide variety of environments; that is, they are more stable in an ionic state than as metals. In thermodynamic terms, there is a net decrease in free energy in going from metallic to oxidized states. Consequently, essentially all metals occur in nature as compounds for example, oxides, hydroxides, carbonates, silicates, sulfides, and sulfates. Two notable exceptions are the noble metals gold and platinum. For them, oxidation in most environments is not favorable, and, therefore, they may exist in nature in the metallic state.

### 10.4 CORROSION RATE

The corrosion rate, or the rate of material removal as a consequence of the chemical action, is an important corrosion parameter. This may be expressed as the **Corrosion Penetration Rate** (CPR), or the thickness loss of material per unit of time. It is given by

$$\text{CPR} = \frac{KW}{\rho At}$$

where,  $W$  is the weight loss after exposure time  $t$ ;  $\rho$  and  $A$  represent the density and exposed specimen area, respectively, and  $K$  is a constant, its magnitude depending on the system of units used. The CPR is conveniently expressed in terms of either mils per year ( $mpy$ ) or millimeters per year ( $mm/yr$ ). As there is an electric current associated with electrochemical corrosion reactions, we can also express corrosion rate in terms of this current or more specifically, current density—that is, the current per unit surface area of material corroding—which is designated  $i$ . The rate  $r$ , in units of  $\text{mol}/\text{m}^2 \text{ s}$ , is determined using the expression

$$r = \frac{i}{nF}$$

where, again,  $n$  is the number of electrons associated with the ionization of each metal atom, and  $F$  is 96,500 C/mol.

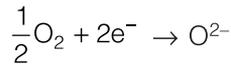
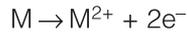
Table : The Galvanic Series

	Platinum
	Gold
	Graphite
	Titanium
	Silver
	316 Stainless steel (passive)
	304 Stainless steel (passive)
	Inconel (80Ni–13Cr–7Fe) (passive)
	Nickel (passive)
	Monel (70Ni–30Cu)
	Copper–nickel alloys
	Bronzes (Cu–Sn alloys)
	Copper
	Brasses (Cu–Zn alloys)
	Inconel (active)
	Nickel (active)
	Tin
	Lead
	316 Stainless steel (active)
	304 Stainless steel (active)
	Cast iron
	Iron and steel
	Aluminum alloys
	Cadmium
	Commercially pure aluminum
	Zinc
	Magnesium and magnesium alloys

Increasingly inert (cathodic) ↑  
↓ Increasingly active (anodic)

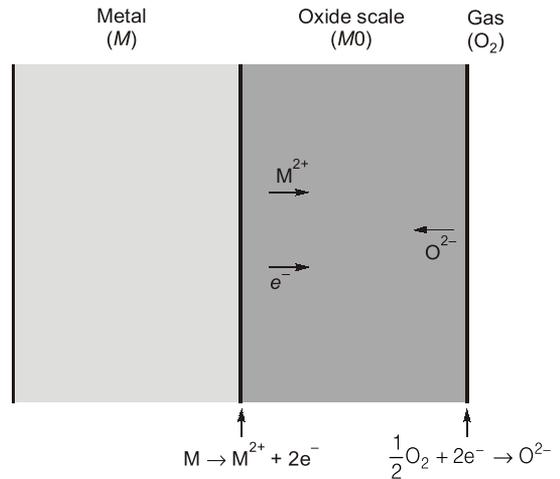
## 10.5 PASSIVITY

Some normally active metals and alloys, under particular environmental conditions, lose their chemical reactivity and become extremely inert. This phenomenon, termed passivity, is displayed by chromium, iron, nickel, titanium, and many of their alloys. It is felt that this passive behavior results from the formation of a highly adherent and very thin oxide film on the metal surface, which serves as a protective barrier to further corrosion. Stainless steels are highly resistant to corrosion in a rather wide variety of atmospheres as a result of passivation. They contain at least 11% chromium that, as a solid-solution alloying element in iron, minimizes the formation of rust; instead, a protective surface film forms in oxidizing atmospheres. (Stainless steels are susceptible to corrosion in some environments, and therefore are not always “stainless.”) Aluminum is highly corrosion resistant



and takes place at the scale–gas interface.

For the oxide layer to increase in thickness, it is necessary that electrons be conducted to the scale–gas interface, at which point the reduction reaction occurs; in addition,  $M^{2+}$  ions must diffuse away from the metal–scale interface, and/or  $O^{2-}$  ions must diffuse toward this same interface. Thus, the oxide scale serves both as an electrolyte through which ions diffuse and as an electrical circuit for the passage of electrons. Furthermore, the scale may protect the metal from rapid oxidation when it acts as a barrier to ionic diffusion and/or electrical conduction; most metal oxides are highly electrically insulative.



**Fig. :** Schematic representation of processes that are involved in gaseous oxidation at a metal surface.



**OBJECTIVE BRAIN TEASERS**

- Q.1** Consider the factors given below:
1. Localised stagnant solution.
  2. Localised depletion of dissolved oxygen.
- Which of the given factors lead/s to crevice corrosion?
- (a) 1 only                      (b) 2 only  
(c) Both 1 and 2              (d) Neither 1 nor 2
- Q.2** Which of the following types of corrosion is difficult to monitor and is very dangerous form of corrosion?
- (a) Pitting                      (b) Stress  
(c) Galvanic                      (d) Crevice
- Q.3** **Statement (I):** As compared to aluminium, iron is considered to be more prone to rusting.  
**Statement (II):** Iron oxidizes more rapidly in comparison with aluminium.
- (a) Both Statement (I) and Statement (II) are individually true and Statement (II) is the correct explanation of Statement (I).  
(b) Both Statement (I) and Statement (II) are individually true but Statement (II) is NOT the correct explanation of Statement (I).  
(c) Statement (I) is true but Statement (II) is false.  
(d) Statement (I) is false but Statement (II) is true.

**ANSWER KEY**

1. (c)    2. (a)    3. (c)

**HINTS & EXPLANATIONS**

1. (c)  
Crevice corrosion is caused as a consequence of concentration difference of ions or dissolved gases. It occurs in the zones where solution is able to penetrate and remain stagnant.
2. (a)  
Pitting corrosion affects metals and alloys such as steel, Iron, Aluminium etc. It is usually constrained to specific areas. It penetrates and attacks rapidly that is why it is difficult to detect.
3. (c)  
The oxidation potential of Al is higher when compared to iron. As a result Al reacts readily with atmospheric oxygen and forms a protective layer of  $Al_2O_3$  which prevents further corrosion of Al.  
On the other hand, the oxide of iron  $Fe_2O_3$ , once formed, only exaggerates further rusting.

