

# Material Science

## Prof. Satish V. Kailas

Associate Professor  
Dept. of Mechanical Engineering,  
Indian Institute of Science,  
Bangalore – 560012  
India

### Chapter 1. Introduction

#### Learning objectives:

To know about

- History of materials origin.
- Properties of materials, and interrelation with influencing factors.
- Different classes of engineering materials.
- Present and future needs of materials.

# Material Science

## Prof. Satish V. Kailas

Associate Professor  
Dept. of Mechanical Engineering,  
Indian Institute of Science,  
Bangalore – 560012  
India

### Chapter 1. Introduction

#### **Highlights, Motivation and Critical Concepts:**

There is undisputable evidence that human race and its social development is very much interwoven with known materials and their use. It is true that we are living in materials world of Electronic/Space Age now, and our ancestors were lived in Stone Age, Bronze Age, followed by Iron Age. Engineering materials are used for different purposes like tools, transportation, decoration, and jewelry. Properties of materials dictate their engineering purpose. Properties of materials are in turn dependent on atomic structure of materials. Other important components of Materials Science along with structure and properties are processing, and performance. Most of the engineering materials in their raw form are not useful, thus need to be processed. Usefulness of a material is dictated by its performance under desired conditions.

# Material Science

## Prof. Satish V. Kailas

Associate Professor  
Dept. of Mechanical Engineering,  
Indian Institute of Science,  
Bangalore – 560012  
India

### Chapter 1. Introduction

#### 1.1 Historical Perspective and Materials Science

##### 1.1.1 Historical Perspective

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.

From the historical point of view, it can be said that human civilization started with *Stone Age* where people used only natural materials, like stone, clay, skin, and wood for the purposes like to make weapons, instruments, shelter, etc. Thus the sites of deposits for better quality stones became early colonies of human civilization. However, the increasing need for better quality tools brought forth exploration that led to *Bronze Age*, followed by *Iron Age*. When people found copper and how to make it harder by alloying, the *Bronze Age* started about 3000 BC. The use of iron and steel, a stronger material that gave advantage in wars started at about 1200 BC. Iron was abundant and thus availability is not limited to the affluent. This commonness of the material affected every person in many aspects, gaining the name *democratic material*. The next big step in human civilization was the discovery of a cheap process to make steel around 1850 AD, which enabled the railroads and the building of the modern infrastructure of the industrial world. One of the most significant features of the *democratic material* is that number of users just exploded. Thus there has been a need for human and material resources for centuries, which still going strong. It's being said and agreed that we are presently in *Space Age* marked by many technological developments towards development materials resulting in

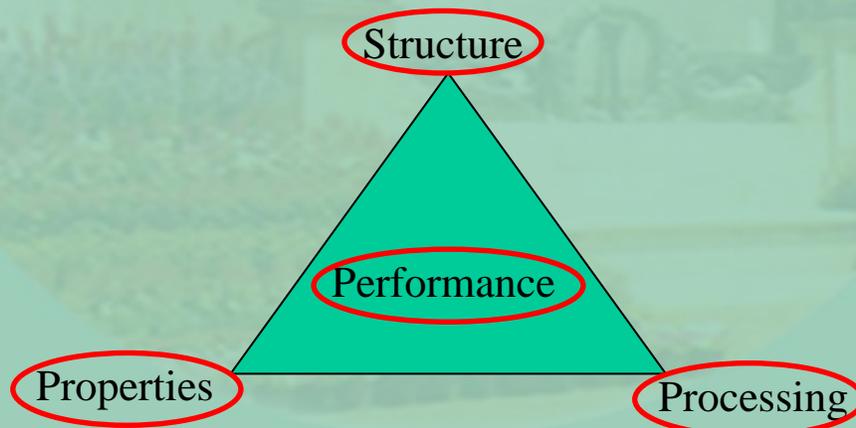
stronger and light materials like composites, electronic materials like semiconductors, materials for space voyage like high temperature ceramics, biomaterials, etc.

In summary, materials constitute foundation of technology. The history of human civilization evolved from the Stone Age to the Bronze Age, the Iron Age, the Steel Age, and to the Space Age (contemporaneous with the Electronic Age). Each age is marked by the advent of certain materials. The Iron Age brought tools and utensils. The Steel Age brought railroads, instruments, and the Industrial Revolution. The Space Age brought the materials for stronger and light structures (e.g., composite materials). The Electronic Age brought semiconductors, and thus many varieties of electronic gadgets.

### ***1.1.2 Materials Science***

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 1.1.



**Figure 1.1:** *Interrelation between four components of Materials Science.*

## **1.2 Why Study Materials Science and Engineering? and Classification of Materials?**

### ***1.2.1 Why Study Materials Science and Engineering?***

All engineers need to know about materials. Even the most "immaterial", like software or system engineering depend on the development of new materials, which in turn alter the economics, like software-hardware trade-offs. Increasing applications of system engineering are in materials manufacturing (industrial engineering) and complex environmental systems.

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 lesson 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.

### ***1.2.2 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.

**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.

**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.

**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.

**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.

**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).

**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.

### 1.3 Advanced Materials, Future Materials, and Modern Materials needs

### **1.3.1 Advanced Materials**

These are materials used in *High-Tech* devices those operate based on relatively intricate and sophisticated principles (e.g. computers, air/space-crafts, electronic gadgets, etc.). These materials are either traditional materials with enhanced properties or newly developed materials with high-performance capabilities. Hence these are relatively expensive. Typical applications: integrated circuits, lasers, LCDs, fiber optics, thermal protection for space shuttle, etc. Examples: Metallic foams, inter-metallic compounds, multi-component alloys, magnetic alloys, special ceramics and high temperature materials, etc.

### **1.3.2 Future Materials**

Group of new and state-of-the-art materials now being developed, and expected to have significant influence on present-day technologies, especially in the fields of medicine, manufacturing and defense. Smart/Intelligent material system consists some type of sensor (*detects an input*) and an actuator (*performs responsive and adaptive function*). Actuators may be called upon to change shape, position, natural frequency, mechanical characteristics in response to changes in temperature, electric/magnetic fields, moisture, pH, etc.

Four types of materials used as actuators: Shape memory alloys, Piezo-electric ceramics, Magnetostrictive materials, Electro-/Magneto-rheological fluids. Materials / Devices used as sensors: Optical fibers, Piezo-electric materials, Micro-electro-mechanical systems (MEMS), etc.

Typical applications: By incorporating sensors, actuators and chip processors into system, researchers are able to stimulate biological human-like behavior; Fibers for bridges, buildings, and wood utility poles; They also help in fast moving and accurate robot parts, high speed helicopter rotor blades; Actuators that control chatter in precision machine tools; Small microelectronic circuits in machines ranging from computers to photolithography prints; Health monitoring detecting the success or failure of a product.

### **1.3.3 Modern Materials needs**

Though there has been tremendous progress over the decades in the field of materials science and engineering, innovation of new technologies, and need for better performances of existing technologies demands much more from the materials field. More over it is evident that new materials/technologies are needed to be environmental friendly. Some typical needs, thus, of modern materials needs are listed in the following:

- Engine efficiency increases at high temperatures: requires high temperature structural materials

- Use of nuclear energy requires solving problem with residues, or advances in nuclear waste processing.
- Hypersonic flight requires materials that are light, strong and resist high temperatures.
- Optical communications require optical fibers that absorb light negligibly.
- Civil construction – materials for unbreakable windows.
- Structures: materials that are strong like metals and resist corrosion like plastics.

## References

1. M. F. Ashby and D. R. H. Jones, Engineering Materials 1, An introduction to Their Properties and Applications, second edition, Butterworth-Heinemann, Woburn, UK, 1996
2. William D. Callister, Jr, Materials Science and Engineering – An introduction, sixth edition, John Wiley & Sons, Inc. 2004.
3. V. Raghavan, Materials Science and Engineering, third edition, Prentice Hall of India Private Limited, New Delhi, 1990.



# Material Science

## Prof. Satish V. Kailas

Associate Professor  
Dept. of Mechanical Engineering,  
Indian Institute of Science,  
Bangalore – 560012  
India

## Introduction

What are materials?  
What is material science?  
Why to study material science?  
How important the materials are?  
Why we use different materials for different purposes?  
What are present and future needs of the materials?  
Want to know how good you are in this chapter?

### What are materials?

That's not difficult. Just look around. Materials are everywhere! The book we are using is made from a variety of materials. The glass in the windows, the aluminium frame, the ceramic dinnerware, the metal silverware and jewelry, automobiles, and everywhere we look we see products made from materials. Most products are made from many different kinds of materials to satisfy the needs of the product.

### What is material science and what we study in that?

The field of Materials Science deals with all classes of materials from a unified viewpoint and with an emphasis on the connections between the underlying structure and the processing, properties, and performance of the material. A materials scientist studies how materials react/ behave when subjected to different conditions (such as mechanical loads, temperature and pressure) and understands that all materials can be approached from a common set of principles. Most fields in science and engineering are concerned in some way or other with materials, but only the field of materials science and engineering focuses directly on them.

### Why to study material science?

Work and study in the field of materials science is anchored around an understanding of why materials behave the way they do, and encompasses how materials are made and how new ones can be developed. For example, the way materials are processed is often important. People in the Iron Age discovered this when they learned that soft iron could be heated and then quickly cooled to make a material hard enough to plow the earth; and the same strategy is used today to make high-strength aluminum alloys for jet aircraft. Today we demand more from our materials than mechanical strength; of course electrical, optical, and magnetic properties, for example, are crucial for many applications. As a result, modern materials science focuses on ceramics, polymers, and semiconductors, as well as on materials, such as metals and glasses, that have a long history of use. In these and other areas of science and technology, materials scientists are indeed key participants.

## How important the materials are?

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.

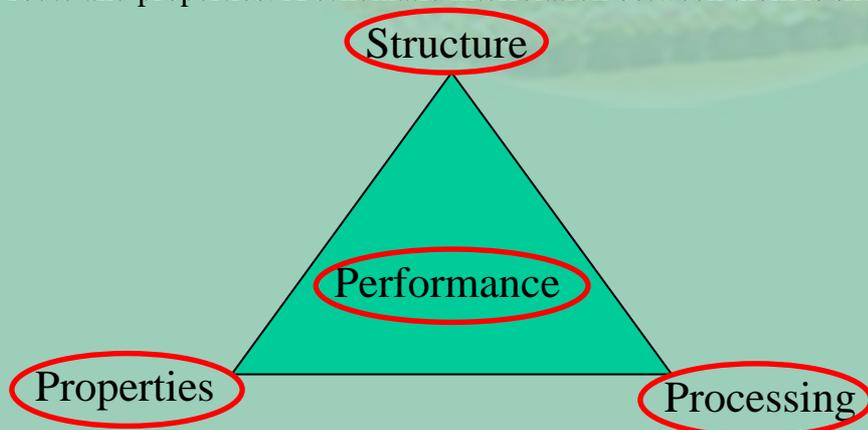
From the historical point of view, it can be said that human civilization started with Stone Age where people used only natural materials, like stone, clay, skin, and wood for the purposes like making weapons, instruments, shelter, etc. Thus the sites of deposits for better quality stones became early colonies of human civilization. However, the increasing need for better quality tools brought forth exploration that led to Bronze Age, followed by Iron Age. When people found copper and how to make it harder by alloying, the Bronze Age started about 3000 BC. The use of iron and steel, a stronger material that gave advantage in wars started at about 1200 BC. Iron was abundant and thus availability is not limited to the affluent. This commonness of the material affected every person in many aspects, gaining the name democratic material.

The next big step in human civilization was the discovery of a cheap process to make steel around 1850 AD, which enabled the railroads and the building of the modern infrastructure of the industrial world. One of the most significant features of the democratic material is that number of users just exploded. Thus there has been a need for human and material resources for centuries, which still going strong. It's being said and agreed that we are presently in Space Age marked by many technological developments towards development materials resulting in stronger and light materials like composites, electronic materials like semiconductors, materials for space voyage like high temperature ceramics, biomaterials, etc.

In summary, materials constitute foundation of technology. The history of human civilization evolved from the Stone Age to the Bronze Age, the Iron Age, the Steel Age, and to the Space Age (contemporaneous with the Electronic Age). Each age is marked by the advent of certain materials. The Iron Age brought tools and utensils. The Steel Age brought railroads, instruments, and the Industrial Revolution. The Space Age brought the materials for stronger and light structures (e.g., composite materials). The Electronic Age brought semiconductors, and thus many varieties of electronic gadgets.

## Why we use different materials for different purposes?

Selection of a material for particular application depends on its performance and economy. Here, we only concentrate on performance. Performance of a material depends on structure, processing route and properties. A schematic interrelation between them is shown in figure 1.1.



**Figure 1.1:** Interrelation between four components of Materials Science.

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).

### How do we differentiate the materials from each other?

Like many other things, materials are classified in groups based on many criteria, for example crystal structure (arrangement of atoms and bonds between them), or properties, or use. In general the materials are classified as Metals, Ceramics, Polymers, Composites, Semiconductors, and

**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.

**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.

**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.

**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.

**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).

**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.

### What are present and future needs of the materials?

**Advanced Materials:** These are materials used in High-Tech devices those operate based on relatively intricate and sophisticated principles (e.g. computers, air/space-crafts, electronic gadgets, etc.). These materials are either traditional materials with enhanced properties or newly developed materials with high-performance capabilities. Hence these are relatively expensive. Typical applications: integrated circuits, lasers, LCDs, fiber optics, thermal protection for space shuttle, etc. Examples: Metallic foams, inter-metallic compounds, multi-component alloys, magnetic alloys, special ceramics and high temperature materials, etc.

**Future Materials:** Group of new and state-of-the-art materials now being developed, and expected to have significant influence on present-day technologies, especially in the fields of medicine, manufacturing and defense. Smart/Intelligent material system consists some type of sensor (detects an input) and an actuator (performs responsive and adaptive function). Actuators may be called upon to change shape, position, natural frequency, mechanical characteristics in response to changes in temperature, electric/magnetic fields, moisture, pH, etc.

**Four types of materials used as actuators:** Shape memory alloys, Piezo-electric ceramics, Magnetostrictive materials, Electro-/Magneto-rheological fluids. Materials / Devices used as sensors: Optical fibers, Piezo-electric materials, Micro-electro-mechanical systems (MEMS), etc.

**Typical applications:** By incorporating sensors, actuators and chip processors into system, researchers are able to stimulate biological human-like behavior; Fibers for bridges, buildings, and wood utility poles; They also help in fast moving and accurate robot parts, high speed helicopter rotor blades; Actuators that control chatter in precision machine tools; Small microelectronic circuits in machines ranging from computers to photolithography prints; Health monitoring detecting the success or failure of a product.

- Engine efficiency increases at high temperatures: requires high temperature structural materials
- Use of nuclear energy requires solving problem with residues, or advances in nuclear waste processing.
- Hypersonic flight requires materials that are light, strong and resist high temperatures.
- Optical communications require optical fibers that absorb light negligibly.
- Civil construction – materials for unbreakable windows.
- Structures: materials that are strong like metals and resist corrosion like plastics.

### Want to know how good you are in this chapter?

1. First material known to be used by man

- (a) Cotton                      (b) Bronze                      (c) Iron                      (d) Rock

2. First metal known to be used by man

- (a) Iron                      (b) copper                      (c) Silver                      (d) Aluminium

3. Which one of the following is not basic component of Materials Science?

- (a) Cost                      (b) Properties                      (c) Structure                      (d) Performance

4. Figure out the odd statement about ceramics in the following

- (a) Good insulators of heat and electricity                      (b) Usually less desire than metals  
(c) Ductile in nature                      (d) Contains both metallic and nonmetallic elements

5. Pick the composite from the list

- (a) Wood                      (b) Steel                      (c) Nylon                      (d) Mica

6. Not an example for actuator

- (a) Optical fiber                      (b) Shape memory alloys  
(c) Magneto-strictive materials                      (d) Electro-/Magneto-rheological fluids

7. Strong and ductile materials

- (a) Polymers                      (b) Ceramics                      (c) Metals                      (d) Semiconductors

8. Presently most used metal in the world

- (a) Aluminium                      (b) Gold                      (c) Steel                      (d) Silver

9. Detrimental property of a material for shock load applications

- (a) High density                      (b) Low toughness                      (c) High strength                      (d) Low hardness

10. Democratic material

- (a) Diamond                      (b) Titanium                      (c) Iron                      (d) Gold

Answers:

1. d

- 2. b
- 3. a
- 4. c
- 5. a
- 6. a
- 7. c
- 8. c
- 9. b
- 10. c

