1

Introduction to Material Science and Metallurgy

Contents

1.1 Introduction to Material Science and Metallurgy

Material is that from which anything can be made. It includes a wide range of metals and non-metals that are used to form the finished product.

Material science is the study of the structure-properties relationship of engineering materials such as ferrous; non-ferrous materials, polymers, ceramics, composites, and some advanced materials.

It is important to study material science because of the following reasons:

- For the selection of material for a particular application based on their performance and cost.
- To understand the limitations of a particular material for different applications.
- To be able to understand the change in the properties of a material with use.
- For creating new material which will have the desired properties.
- Metallurgy is the study of metals related to their extraction from ore, refining, production of alloys along with their properties.
- The scientific methods are used to evaluate, plan, produce a perfect metallurgical process.

A metallurgical field may be classified as follows:

1. Extractive Metallurgy
2. Mechanical Metallurgy
3. Physical Metallurgy

Extractive metallurgy is the branch that deals with the separation of metals by various Chemical processes from the ores.

- Mechanical metallurgy deals with the mechanical working as well as testing of mechanical properties of materials.
- Physical metallurgy deals with the structures of metals and alloys after deformation and treatment of metals.
- Hence, the study of material science and metallurgy links the science of metals to the industries.

Also, this helps in completing demands from new applications and severe-service requirements.

1.2 Classification of Materials

Most engineering materials may be classified into the following types

a) Metals (Ferrous and Non-ferrous)
b) Ceramics
c) Composite
d) Semiconductors
e) Organics
f) Advanced materials

a) Metals

- Metals are very important in the industrial application and play a major role in the day-to-day life of human beings.
- There are many metal parts and objects, which are used in engineering applications.
- The commonly used metal are Iron, Aluminium, Copper, Magnesium, etc

b) Ceramics

- Ceramics generally consist of oxides, nitrides, carbides, silicates or borides of various metals.
- Ceramic materials contain compounds of metallic and non-metallic elements such as MgO, SiO_2, Sic, glasses, etc.
- Ceramics are any inorganic, non-metallic solids, processed or used at high temperatures.
- The commonly used ceramic materials are Sand, Cement, Abrasive, Glass, Concrete, Plaster, etc

c) Organics

- Organics are polymeric materials composed of carbon compounds. (Polymers are solids composed of long molecular chains).
- Organic materials may be natural, synthetic or manufactured and based chemically on carbon.

  The commonly used organics are Rubber, Plastics, Lubricants, Wood, Textiles, Fuels, etc.

d) Composites

- Composite materials consist of more than one material type.
- For example, fiber-glass in which glass fibers are embedded within a polymeric material.

e) Semiconductors

- Semiconductors have electrical properties that are intermediate between the electrical conductors and insulators.
- The electrical characteristics of these materials are extremely sensitive to the presence of minute concentrations of impurity atoms, of which concentrations may be controlled over very special regions.

f) Advanced Materials

- Advanced materials are used in advanced or high technology applications.
- They consist of newly developed properties.
- These materials are used in the field of telecommunication, computers, aeronautics, electronics, etc.
- Advanced materials are Biomaterials, Nanomaterials, magnetic materials, High and low-temperature material, Dielectric materials, Cryogenics material, etc.

1.3 Selection of Materials

The selection of materials and the manufacturing processes are integral parts of the design of a machine element. In fact, the design of any machine element begins with the selection of material.

There are a large number of engineering materials available and many more are adding up day by day. The material selection is not an easy job and involves the trial and error method.

- The choice of the materials depends upon the following factors:

1. Availability of materials

- The materials which are available readily and in abundance in the market should be selected.
- As far as possible, the materials which are not available easily should be avoided.

2. Cost of material

- In today’s world of competition, cost plays a significant role in the success of the product.
- The material should be selected such that the total cost should be minimum and within the specified limit.

- The total cost includes the cost of material and the cost of processing the material.

3. **Manufacturing considerations**

- The manufacturing considerations play a vital role in material selection. The selected material should be suitable for the required manufacturing processes.
- For example, if the body of the machine is to be made by the casting process, the material suitable for the casting process must be selected.
- However, if the material is found suitable for all other considerations, sometimes the manufacturing process can be changed, if feasible.

4. **Material properties**

- The material properties, in general, and mechanical properties, m particular, govern the selection of the materials.
- The different mechanical properties considered are static strength, fatigue strength, stiffness, elasticity, plasticity, ductility, brittleness, malleability, hardness, toughness, resilience, creep, etc.

1.4 Engineering Requirements of Materials

Nowadays there is a tremendous increase in the availability of materials along with demands from various applications and service conditions.

- Materials should fulfill the engineering requirements so that they can be successfully used for making various components.
- The properties of the selected material help the component to perform its operation successfully while in use.
- The following are the various engineering requirements which material should fulfill
  a) Fabrication requirements
  b) Service requirements
  c) Economic requirements

1. **Fabrication requirements**

- These requirements include the ability of the material to be able to get shaped or machined by various forming and manufacturing processes. For example, casting, forging, machining, sintering, etc.
- Also, the material should be able to join easily by welding, brazing, etc.
- The properties of materials such as machinability, ductility, castability, weldability, heat-treatability, etc. are related to fabrication requirements.

2. **Service requirements**

- The material selected for the particular application should withstand all the service demands and severe service conditions.
- Selected material for a component should function properly during the service life of the component.
- Properties of materials such as strength, toughness, wear resistance, corrosion resistance, etc. are related to the service requirements.

3. **Economic requirements**

- This demand implies that the component should be made from the material at the minimum possible cost.
- All the variables should be properly selected to achieve optimum cost and quality of a material.

- Both technical and marketing parameters should be selected properly for the minimum overall cost.

1.5 Properties of Materials

Property of a material is a factor that influences qualitatively or quantitatively the response of a given material under the action of forces, temperatures, pressures, etc.

- The property indicates that, whether a material is suitable or unsuitable for particular use in industry.
- The material property is independent of the dimension or shape of the material.
- The various material properties are divided into the following groups:
  1. Mechanical Properties
  2. Thermal Properties
  3. Electrical Properties

Mechanical Properties

- Mechanical properties include those characteristics of a material that describe its behavior under the action of external forces.
- The knowledge of the mechanical properties of materials is very essential in order to construct a mechanically fool-proof structure.

Some of the important mechanical properties are as follows:

1. Elasticity	2. Plasticity	3. Toughness	4. Resilience
5. Strength	6. Stiffness	7. Ductility	8. Malleability
9. Brittleness	10. Brittleness	11. Fatigue	12. Creep
13. Weldability	14. Formability	15. Machineability	

1. Elasticity

- It is the property of a material to regain its original shape after deformation when the external forces are removed.
- This property is required for materials used in tools and machines.
- It is important to note that, steel is more elastic than rubber.

2. Plasticity

- The property of a material that retains the deformation produced under the load permanently is called plasticity.
- This property is essential in stamping, press work, forgings, ornamental work, etc.

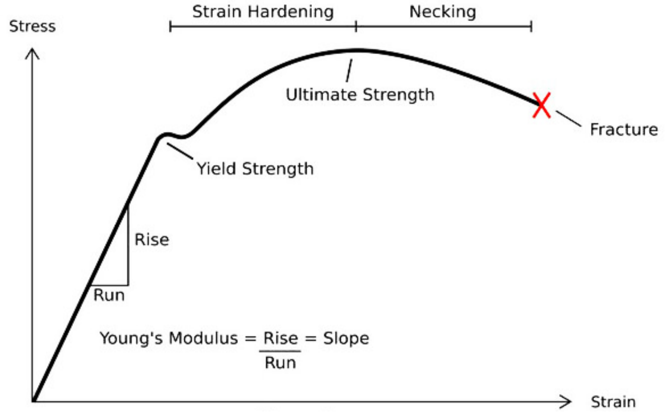

Fig.1.1 – Stress Starin Diagram For Material

3. **Toughness**

- Toughness is the total amount of energy absorbed by the material before its failure.
- It is the complete area under the stress-strain curve i.e. summation of the elastic and plastic region.
- This property is essential in parts subjected to shock and impact loads.

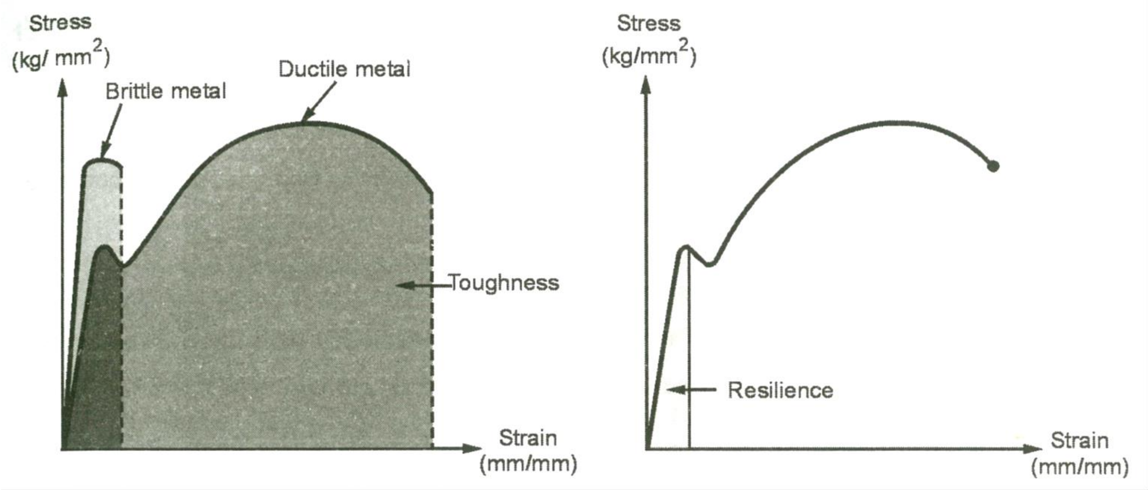

Fig.1.2 – Toughness and Resilience

4. **Resilience**

- The resilience of a material is defined as the total amount of energy absorbed by the material during its elastic deformation.
- This property is essential for springs, shock absorbers, etc.
- The area under the stress-strain curve in the elastic region indicates resilience.

5. **Strength**

- It is the ability of a material to resist the externally applied forces without failure.
- It is measured in kg/mm^2 or N/mm^2.

6. **Stiffness**

- It is the ability of a material to resist deformation under stress.
- It is also defined as the force or load per unit deflection. It is measured in N/mm.

7. **Ductility**

- It is defined as the ability of a material to undergo plastic deformation under tensile loading, before its fracture.
- Also, ductility is the property of a material by which it can be drawn into fine wires. For example, a rubber.

8. **Malleability**

- It is defined as the ability of a material to be formed by hammering or rolling.
- It is the capacity of a material to withstand deformation under compression without failure.
- The main difference between ductility and malleability is that the ductility is considered as tensile property and malleability is considered as compressive property.

9. Brittleness

- lt is the property of breaking of a material with little permanent distortion.
- Brittleness of material is opposite to ductility. For example glass, concrete block, etc.

10. Hardness

- It is an important property of metals.
- It is defined as the resistance of metal to plastic deformation usually by indentation.
- It is also defined as resistance to scratch, abrasion or cutting.

11. Fatigue

- When a material is subjected to repeated stresses or loading, it fails at stresses below the yield point stress. Such type of failure of material is called fatigue.
- Fatigue failure is caused by means of a progressive crack formation which is generally of microscopic size.
- It is considered while designing shafts, gears, springs, etc.

12. Creep

- When a material is subjected to constant stresses at high temperatures for a long period of time, it will undergo a slow and permanent deformation which is called creep.
- It is considered while designing boilers, I. C. engines, pumps, turbines, etc.

13. Weldability

- Weldability is defined as the capacity of a material to be welded under fabrication conditions imposed in a specific and suitably designed structure and to perform satisfactorily in the intended service.
- It indicates that metal with good weldability can be welded readily so as to perform satisfactorily in the fabricated structure.

Weldability includes,

- Metallurgical compatibility of a metal.
- The ability of the metal or alloy to be welded with mechanical soundness.
- Serviceability of the resulting welded joint.

14. Formability

- It is defined as the property of a material to be formed by compressive or tensile forces in tool and die arrangement.
- This term is generally used for sheet forming processes like bending, stamping, stretch forming, deep drawing, etc.

15. Machineability

- The machinability of a material indicates how machinable the material is.

When it is stated that material P is more machinable than material Q, it means that,

- Less power is required to machine material P.
- Lower tool wear is obtained with material P.
- Better surface finish can be achieved with material P.

- Machinability is also defined as the property of the material which governs the ease or difficulty with which it can be machined under a given set of conditions.

1.6 Structure - Properties - Performance Relationship

The structure - properties - performance relationship forms the basis for optimum selection of material for a particular task.

- The optimum solution for material selection for product and system performance depends upon the properties of a material.
- These properties are related to the internal structure of a material. Hence the structure and properties of the and performance are correlated.
- The structure must be controlled to ensure the desired properties of materials which in tum influence the performance of the system.
- This co-relationship is important and must be considered during both processing steps of production and in service.
- On the other hand, during processing and service, there IS a change in properties of materials due to altered internal structure.
- The performance of a material depends on the internal structure of the component.
- These internal arrangements involve electrons, atoms crystals, and microstructures. The properties of material originating from the internal structures of that material.

1.7 Levels of Internal Structure

The structure is the heart of the material science that connects processing methods of materials with its properties.

- Also, it is the spatial distribution of things seen and unseen in a material.

The following are the levels of internal structure required to study the various materials:

a) Nuclear structure
b) Atomic structure
c) Molecular structure
d) Microstructure
e) Macrostructure

a) Nuclear structure

- It determines the nuclear properties of a material.
- Nuclear structure studies the properties of nuclei in terms of nuclear mass and shapes, characteristic energy levels and radioactive decay.
- These structures can be studied by Nuclear Magnetic Resonance (NMR) spectroscopy, laser spectroscopy, Mossbauer studies, etc.
- These methods are used to identify nuclear ground-state properties like masses, charge radii, spins and moments, etc.

b) Atomic structure

- The atomic structure of any material is an important factor in understanding the physical and chemical properties.

- Also, the properties of materials can be altered by manipulating the position of the atoms or substituting any other atom.
- Atoms and atomic arrangements constitute the •building blocks of advanced materials.
- X-ray crystallography, spectroscopy techniques are used to determine atomic structures.

c) Molecular structure

- Molecules are made up of the number of atoms joined together by a covalent bond.
- The geometrical structure of the molecule is one of the most important and fundamental parameters in distinguishing the materials.
- Molecular spectroscopy, electron gas diffraction, etc. techniques are used to reveal molecular structure.

d) Microstructure

- Microstructure IS defined as the structure of material ranges between 0.1 to 100.
- It is revealed by a microscope above 25X magnification and can strongly influence the physical properties such as strength, toughness, ductility, high/low-temperature behavior, etc.
- The microstructure is usually related to the grain size. The grains and grain boundaries seen in the micrograph •are part of the microstructure.
- Microstructure examination involves higher power techniques such as optical microscopy, electron microscopy, X-ray diffraction, etc.

e) Macrostructure

- Macrostructure is defined as the structure that is revealed by visual examination with little or no magnification. It ranges from 100 and above.
- It is revealed either by machining or by macro etch test.
- The study of macrostructure gives an idea about discontinuities in metal such as cavities, porosity, gas bubbles, etc.
- Also, it reveals the distribution of impurities and non-metallic inclusions, shape, and distribution of grains in various parts of the component.

1.8 References

Sidney H Avner “Introduction to Physical metallurgy” 2nd Edition 2011 Tata Mc Graw- Hill Publication.

O. P. Khanna “Material Science and Metallurgy” Dhanpat Rai Publications.