

General Introduction

Conventional engineering materials metals, polymers, and ceramics each satisfy a limited set of performance requirements. Metals such as steel and aluminium alloys provide high strength and stiffness, but their elevated density penalises applications where weight reduction is critical. Polymers offer low density and good corrosion resistance, yet they cannot sustain the mechanical loads demanded by primary structural components. Ceramics withstand extreme temperatures but are inherently brittle and prone to catastrophic fracture under impact. This fundamental trade-off between competing properties drives the need for a different class of engineering materials capable of combining advantages that no single conventional material can deliver simultaneously [1], [3].

Composite materials address this need. A composite is an engineered material formed by combining two or more chemically distinct constituents at the macroscopic scale. These constituents remain physically identifiable within the final structure and do not dissolve into one another, yet they work together to produce enhanced or tailored properties unattainable by any constituent alone. This capacity for property combination enables composites to achieve high specific strength, high specific modulus, corrosion resistance, and thermal stability that surpass those of conventional metals and unreinforced polymers [3], [4].

The use of composite materials dates back thousands of years through natural examples such as wood, bone, and straw-reinforced mud bricks. Modern synthetic composites emerged in the 1930s with glass fibre reinforced polymers (GFRP), followed by higher-performance carbon and aramid fibre systems in the 1960s–1970s. The field has since expanded to include ceramic matrix composites, hybrid composites, and smart composites with embedded sensing capabilities [3], [5].

Today, composites are widely used in aerospace primary structures, automotive body panels, wind turbine blades, marine hulls, civil infrastructure retrofitting,

sports equipment, and biomedical implants. Their growing adoption is driven by the demand for lightweight, durable, and efficient engineering solutions where reducing structural mass translates directly into improved performance and reduced operational cost [1], [4].

This course is organised in five chapters. Chapter 1 reviews the principal classes of engineering materials and the structure–property–processing–performance relationships. Chapter 2 defines composite materials, their constituents, and classification systems. Chapter 3 the physical and mechanical properties of composites. Chapter 4 covers the main manufacturing processes and associated quality control methods. Chapter 5 addresses material selection for practical engineering design.

Chapter 1: Generalities on Engineering Materials

Contents

Chapter 1: Generalities on Engineering Materials	3
1.1 Introduction to Materials Science	4
1.2 Classification of Engineering Materials.....	5
1.3 Properties of Engineering Materials.....	7
A. Physical Properties	7
B. Mechanical Properties	8
C. Thermal Properties	10
D. Electrical Properties	12
References	13

1.1 Introduction to Materials Science

materials science investigates the relationship between the internal organization of a material (such as atomic bonding, crystal structure, and grain morphology) and its actual engineering behavior. This field relies on the interaction among four key variables represented by the "materials science tetrahedron": processing, structure, properties, and performance (Figure 1.1) [1], [2]. Consequently, selecting materials for engineering applications requires a careful balance between the material's properties, its operating conditions, and its manufacturing costs [1].

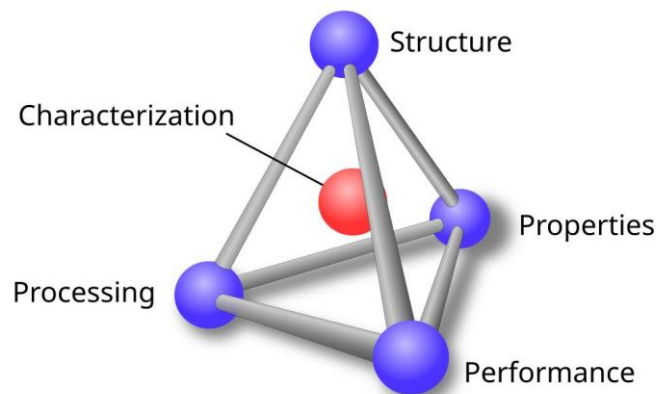


Figure 1.1 Materials Science Tetrahedron showing the interconnected relationship between Processing, Structure, Properties, and Performance

In composite materials engineering, this framework acquires additional complexity. The performance of a composite depends not only on the intrinsic properties of its constituents but also on design variables absent in monolithic materials: reinforcement type and form, volume fraction, stacking sequence, and interfacial bonding quality. This allows the engineer to construct the property set itself rather than select from pre-existing options [1], [3].

1.2 Classification of Engineering Materials

Engineering materials are commonly classified into four major families (Figure 1.2): metals and alloys, polymers, ceramics and glasses, and composite materials. This classification is based primarily on the nature of atomic bonding, chemical composition, and the resulting physical and mechanical properties [1], [2].

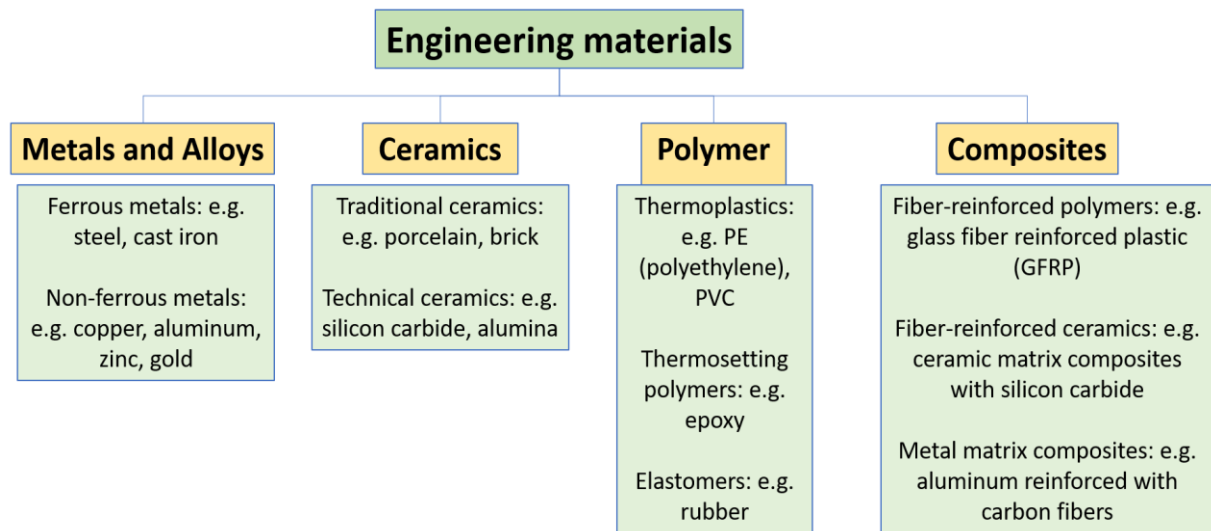


Figure 1.2 — General classification of engineering materials

Metals and alloys are held together by metallic bonding Figure 1.3, in which positively charged ions share a delocalised electron cloud. This structure gives metals their characteristic high strength, stiffness, electrical and thermal conductivity, and capacity for plastic deformation. Steel, aluminium alloys, and titanium alloys are the most widely used structural metals, though their relatively high density and susceptibility to corrosion remain persistent limitations [2].

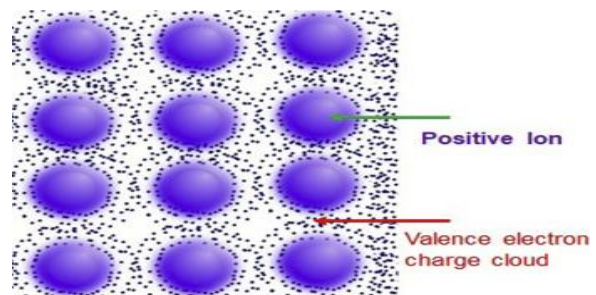


Figure 1.3 Metallic Bonding

Polymers consist of long molecular chains with strong covalent bonds along the backbone and weaker secondary bonds between chains Figure 1.4 . They offer low density, good chemical resistance, and ease of processing, but at significantly lower strength, stiffness, and operating temperatures compared with metals. They are classified as thermoplastics, which can be reshaped by reheating, or thermosets, which undergo irreversible cross-linking during curing [2].

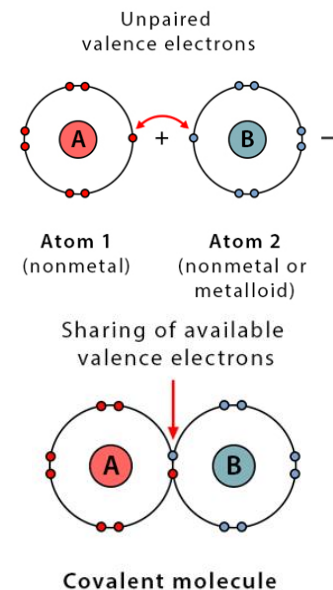


Figure 1.4 Covalent Bonding

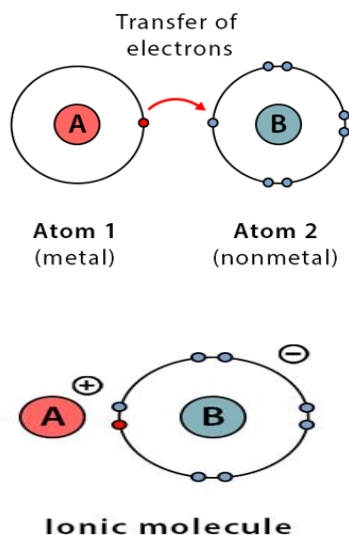


Figure 1.5 Ionic Bonding

Ceramics and glasses are formed by ionic or covalent bonding Figure 1.5, producing materials with high hardness, excellent thermal stability, and strong chemical resistance. They can operate at temperatures far exceeding the limits of metals and polymers; however, their inherent brittleness and low tolerance to tensile or impact loading restrict their use to applications where these weaknesses can be managed through design [1].

Composite materials combine constituents from two or more of the preceding families to achieve property combinations that no single material class can provide alone. Their position in this classification is unique because their properties are not fixed by composition alone but can be engineered through the selection of matrix and reinforcement types, their proportions, and the architecture of the reinforcement phase [1], [3].

1.3 Properties of Engineering Materials

The selection and application of engineering materials depend strongly on their physical, mechanical, thermal, electrical, and chemical properties. These properties describe how a material responds to external conditions and determine its suitability for a specific engineering application [1], [2].

A. Physical Properties

Physical properties describe the intrinsic characteristics of a material that are independent of applied loading or external fields [1], [2].

- **Density** is the mass per unit volume and directly influences the weight of structural components. As shown in Figure 1.6, engineering materials span a wide density range: metals such as steel ($\sim 7.8 \text{ g/cm}^3$) and aluminium ($\sim 2.7 \text{ g/cm}^3$) are considerably denser than polymers ($\sim 0.9\text{--}1.4 \text{ g/cm}^3$), which explains the growing interest in lightweight alternatives for transportation and aerospace applications.

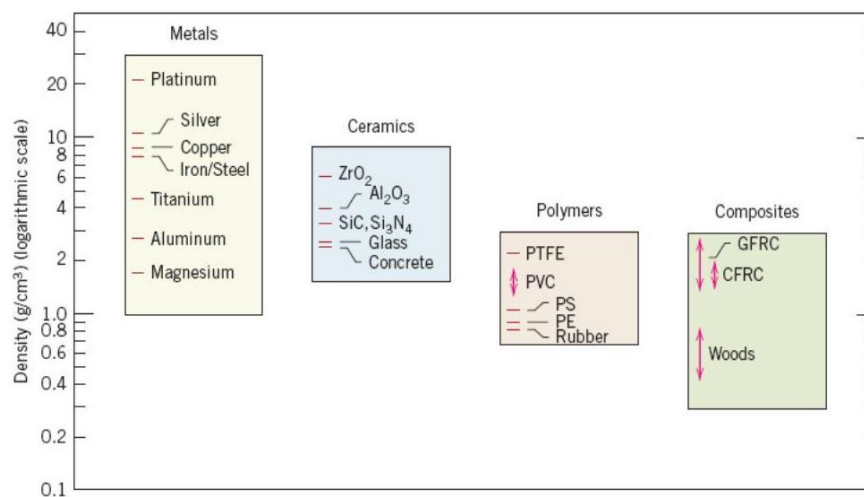


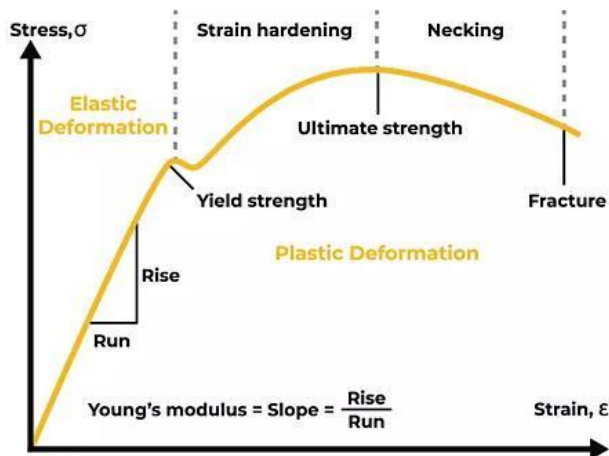
Figure 1.6— Density ranges for the principal engineering material families.

- **Melting point** determines the maximum temperature at which a material retains its solid-state integrity. Refractory ceramics and tungsten alloys melt above 2500°C , whereas most thermoplastics soften below 300°C [2].

B. Mechanical Properties

Mechanical properties characterise how a material responds to externally applied forces and are the primary criteria in structural design [2].

- **Strength** is the maximum stress a material can sustain before failure, measured under tension, compression, or shear depending on the service mode. As illustrated in Figure 1.7, the stress–strain curve provides valuable information about strength, stiffness, and ductility.
- **Stiffness**, quantified by the elastic modulus (Young's modulus), describes the resistance to elastic deformation; the slope of the linear elastic region shown in Figure 1.7 corresponds to the elastic modulus of the material.



Tensile test results.



Figure 1.7— Stress–strain behaviour and mechanical testing of engineering materials.

- **Toughness** is the total energy absorbed before fracture and reflects the combined effect of strength and ductility. As shown in Figure 1.8, ceramics exhibit high strength but fail abruptly with minimal plastic deformation (brittle fracture), whereas metals such as low-carbon steel undergo significant plastic deformation before failure (ductile fracture), resulting in considerably

higher toughness. Unreinforced polymers, by contrast, display large strains at relatively low stress levels, with toughness that varies widely depending on the polymer type and testing conditions

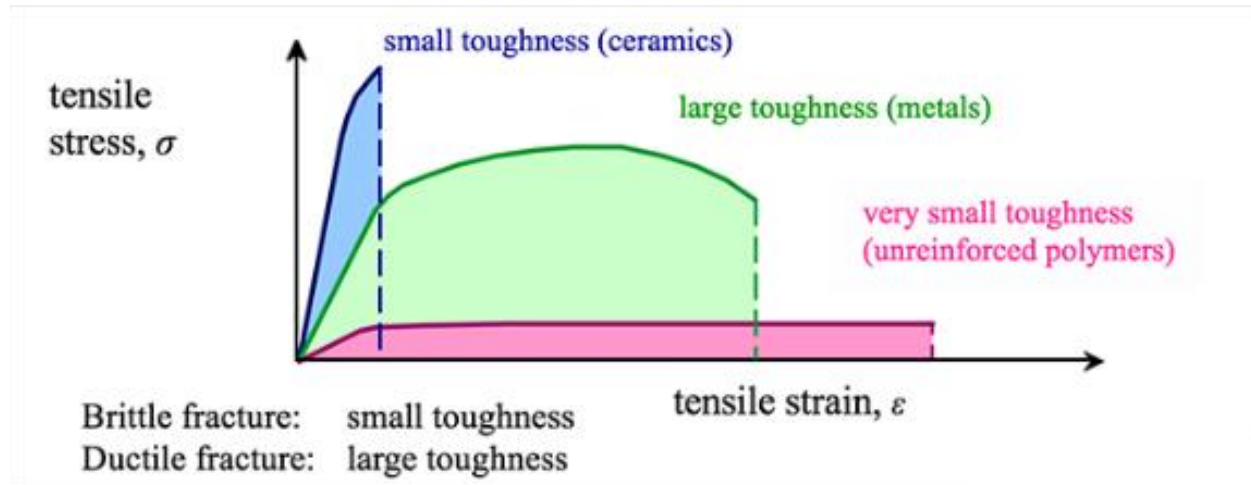


Figure 1.8 Comparative stress–strain curves for ceramics, metals, and unreinforced polymers, illustrating the contrast between brittle and ductile fracture behaviour.

- **Hardness** measures resistance to localised surface deformation and correlates directly with wear resistance *Figure 1.9*.

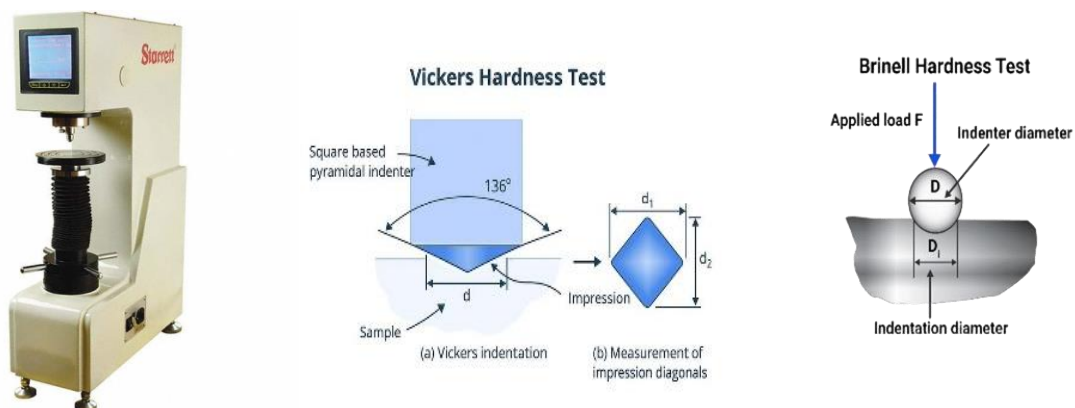


Figure 1.9 Common hardness testing methods used in materials engineering.

- **Fatigue resistance** describes the ability of a material to endure repeated cyclic loading without crack initiation and propagation to failure. As illustrated in Figure 1.10, the S–N curve (stress versus number of cycles) characterises the fatigue behaviour of a material: some metals, such as steel, exhibit a distinct endurance limit below which failure does not occur, whereas aluminium alloys

and most polymers show a continuous decline in allowable stress with increasing cycle count. rotating shafts, bridges, and mechanical springs [2].

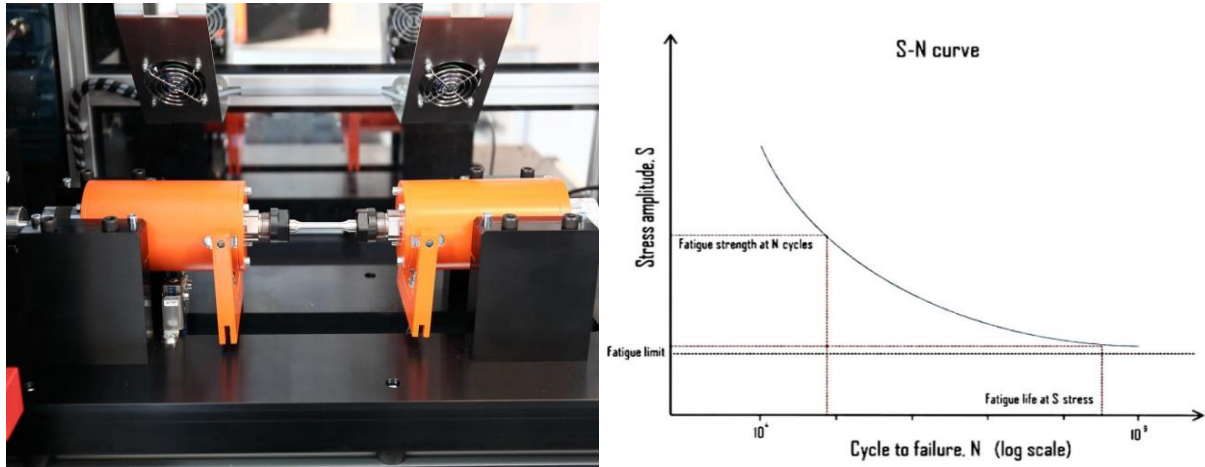


Figure 1.10 Typical $S-N$ fatigue curves and rotating beam fatigue testing setup.

C. Thermal Properties

Thermal properties govern how a material responds to temperature variations and heat flow [1].

- **Thermal conductivity** quantifies the rate of heat transfer under a temperature gradient. As shown in Figure 1.11.

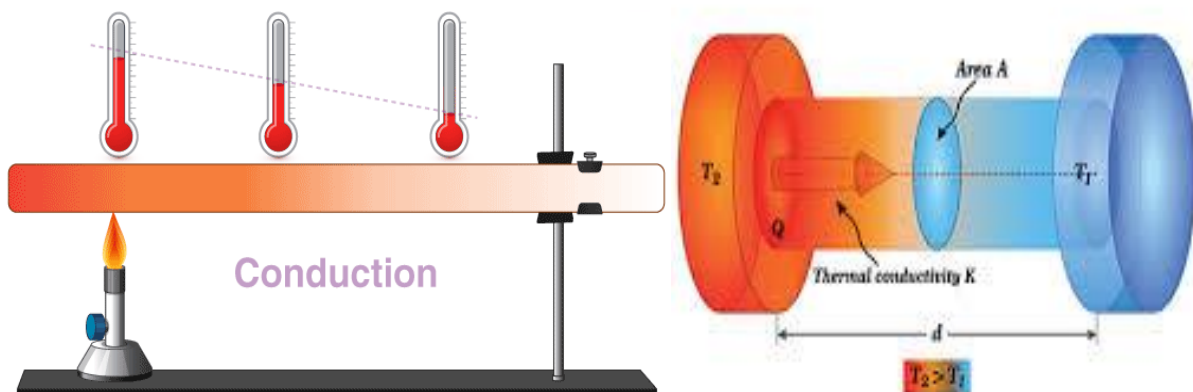


Figure 1.11 Thermal conductivity.

- **Thermal stability** refers to the ability of a material to retain its properties at elevated temperatures. Ceramics maintain structural integrity well above 1000 °C, whereas most polymers degrade between 100 °C and 300 °C Figure 1.11.

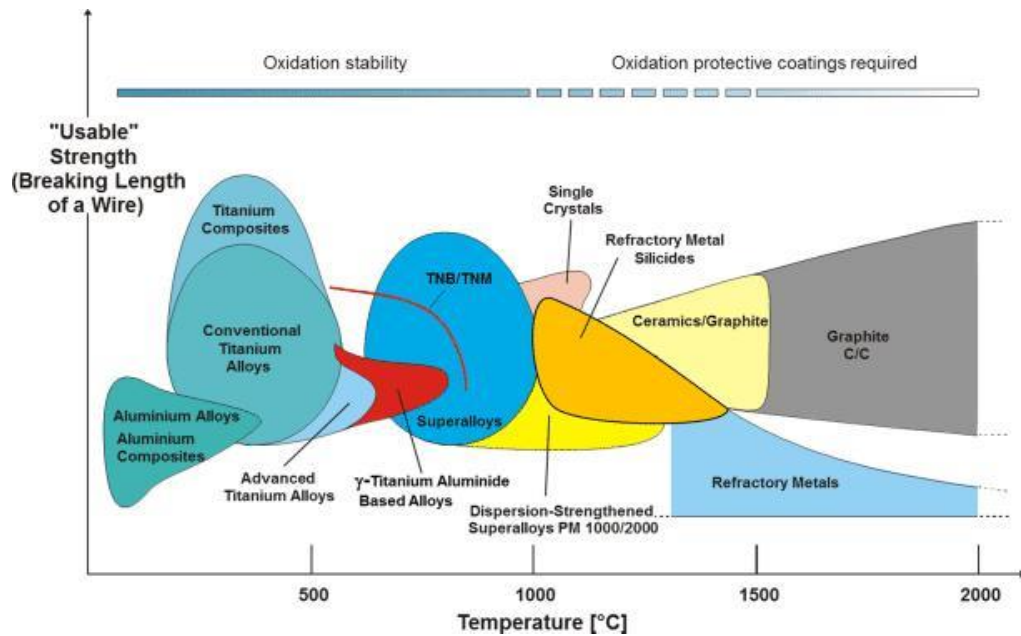


Figure 1.11 — Temperature operating limits for the principal engineering material families.

- **Thermal expansion** is the dimensional change caused by temperature variation

Figure 1.12. Mismatched expansion coefficients between joined materials can generate internal stresses leading to distortion or interfacial failure [1].

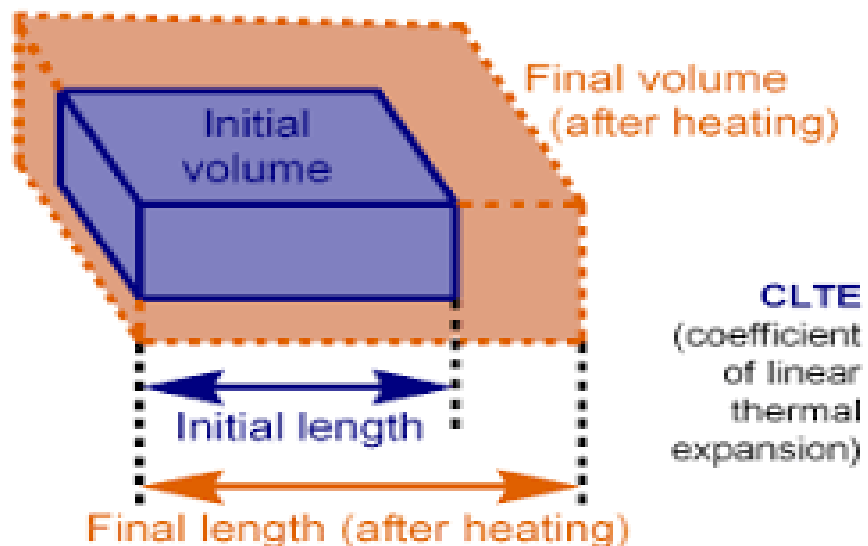


Figure 1.12 — Thermal expansion

D. Electrical Properties

Electrical properties define how a material interacts with electric fields and current flow [2].

- **Electrical conductivity** measures the capacity to transport charge carriers,
- **electrical resistivity** quantifies the opposition to that transport.

As shown in Figure 1.13, these properties span a vast range across material families: metals exhibit high conductivity, semiconductors occupy an intermediate range, and ceramics and polymers function as electrical insulators.

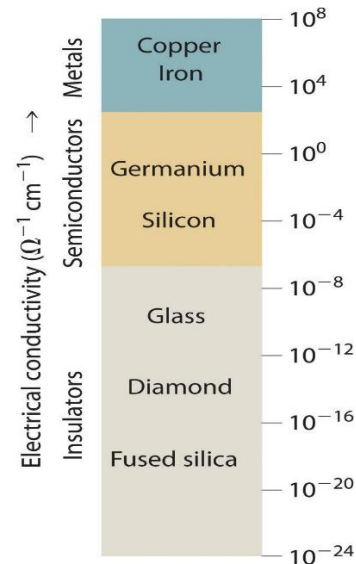


Figure 1.13 — Electrical conductivity spectrum for metals, semiconductors, and insulators.

- **Dielectric behaviour** describes the response of a non-conducting material to an applied electric field and determines its suitability as an electrical insulator or capacitor medium. This property is particularly relevant in electronic packaging, power transmission insulation, and sensor applications *Figure 1.14*.

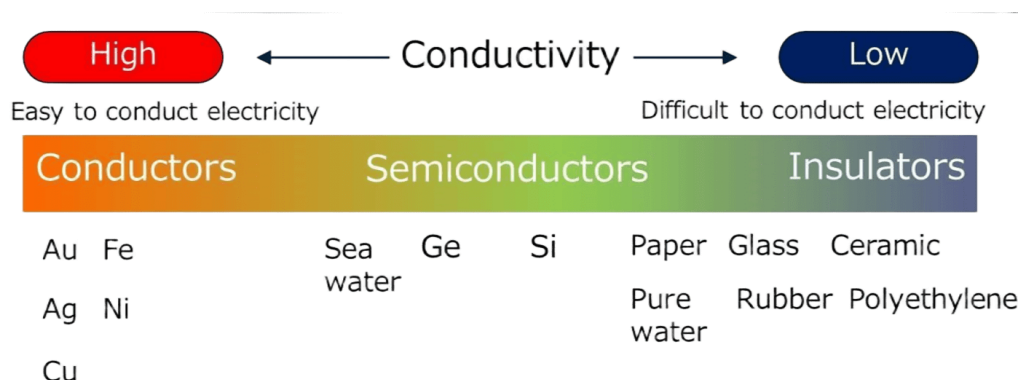


Figure 1.14 — Classification of materials based on electrical behaviour: conductors, semiconductors, and insulators.

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