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Engineering Chemistry

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Module 6-High Performance Materials

Disclaimer

This document is a faculty-curated academic resource created to support and enhance the teaching-learning process.

It is intended to supplement the prescribed textbooks and classroom discussions, offering students an accessible and structured reference for better understanding of the subject.

The content has been thoughtfully compiled by the course faculty using a variety of sources, including standard textbooks, academic references, and available online materials.

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We hope this material serves as a helpful guide in your learning journey.

By the end of this chapter, students will be able to:

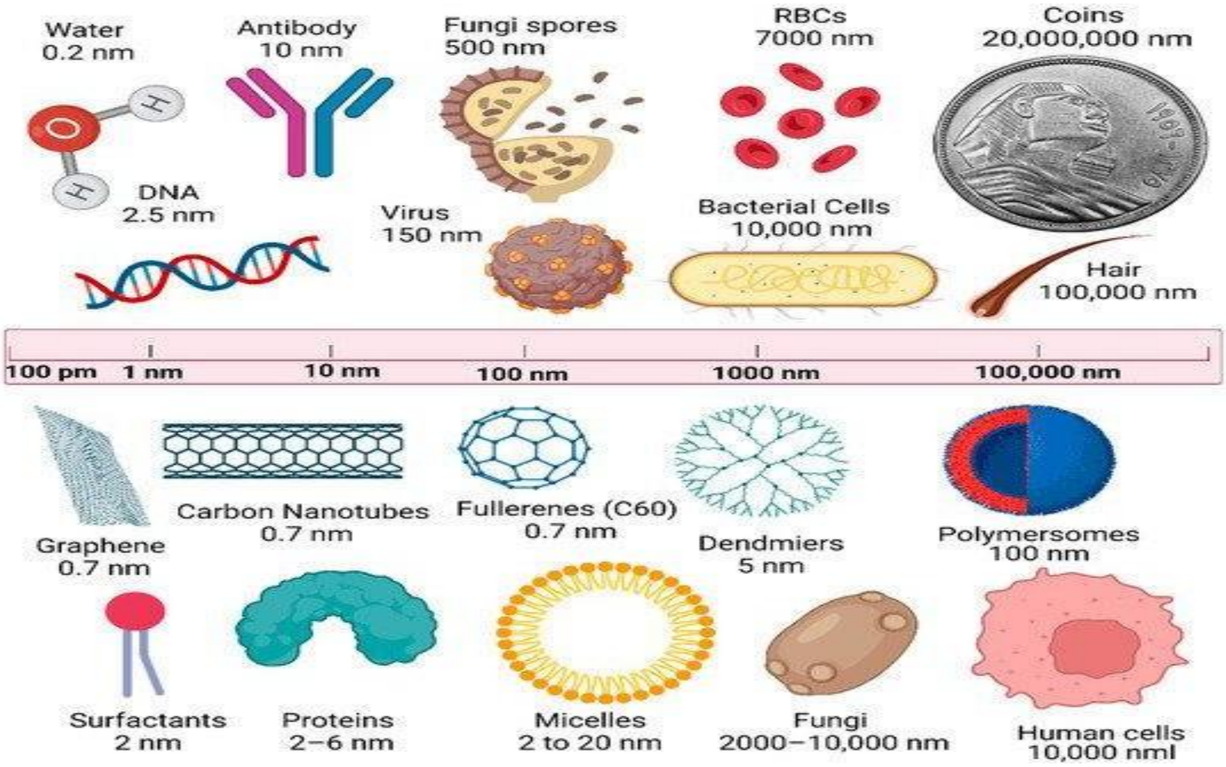
1. Define nanomaterials, composites, and ceramics, and recall their key characteristics and applications.
2. Identify types of nanostructured materials, graphene, carbon nanotubes (SWCNTs and MWCNTs), and common engineering ceramics like alumina, silicon carbide, and zirconia.
3. Explain the synthesis of carbon nanotubes using Chemical Vapor Deposition and describe the roles of matrix and dispersed phase in composites.
4. Distinguish composite materials from conventional materials and summarize classifications such as polymer composites and biocomposites.
5. Apply knowledge of catalyst size, temperature, and carbon sources to predict CNT type and growth outcomes.
6. Illustrate practical uses of composites and ceramics in engineering contexts.
7. Compare SWCNTs and MWCNTs in terms of structure, properties, and applications.
8. Analyze differences between polymer composites, biocomposites, and ceramic composites based on their components and performance.
9. Propose suitable nanomaterials or composite systems for specific applications, integrating matrix and dispersed phase selection.
10. Evaluate the effectiveness of CNTs, graphene, composites, and ceramics in advanced applications such as electronics, energy storage, and high-temperature environments.

Nanomaterials

6.1-Definition

Nanomaterials are materials that have at least one dimension in the nanoscale range **1–100 nm**, giving them unique physical, chemical and mechanical properties.

Different Nanosized Materials



Nanoscience:

Studies how materials behave at the nanoscale using physics, biology, and chemistry

Nanotechnology:

Involves measuring, manipulating, and creating materials at the nanoscale for practical use

Basic Features

Materials with at least one dimension between 1–100 nm

"Nano" means very small (10^{-9} m)

Exhibit unique properties due to quantum and surface effects

Differ from bulk materials in size, shape, composition, and porosity

Widely used in electronics, medicine, energy, and material science

6.1.1-Classification of Nanomaterials

Based on number of dimensions in the nanoscale (Siegel's classification):

Type of Nanomaterial	**Dimensions in Nanoscale**	**Shape / Structure**	**Examples**
0D (Zero-Dimensional)	All 3 dimensions (x, y, z) < 100 nm	Spherical / cluster-like	Nanospheres, Nanoclusters
1D (One-Dimensional)	2 dimensions < 100 nm; 1 dimension > 100 nm	Rod / fibre / tube-like	Nanotubes, Nanowires, Nanorods, Nanofibres
2D (Two-Dimensional)	1 dimension < 100 nm; 2 dimensions > 100 nm	Sheet / plate-like	Nanofilms, Nanolayers, Nanocoatings
3D (Three-Dimensional)	No dimension < 100 nm (but built from nanoscale units)	Bulk nanostructures / aggregates	Nanoparticle dispersions, Bundles of nanotubes/nanowires, Polycrystalline nanomaterials

Quantum confinement:
In how many dimension it is confined:
Quantum dots: confined in all 3 dimension
Nanotubes: confined in 2 dimension
Nanaolayers: confined in 1 dimension

Dimension of nanomaterials:
0D nanomaterials: confined to nanoscale in all dimension. E.g. quantum dots

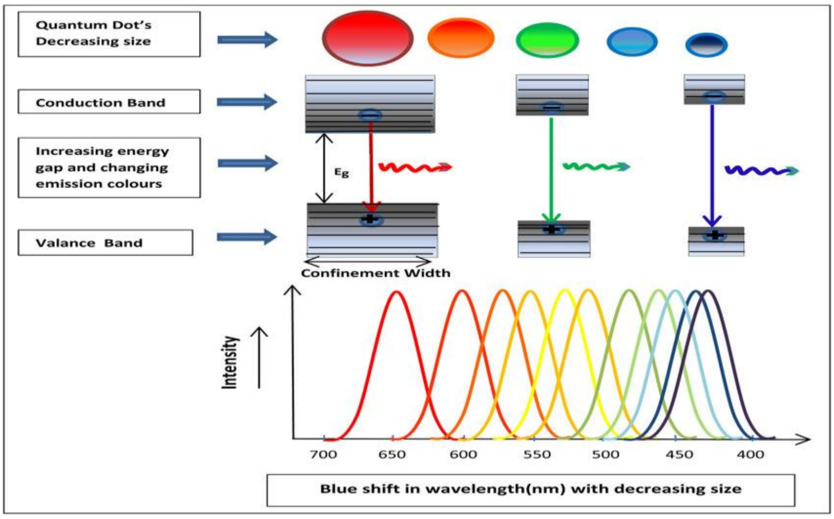
1D nanomaterials: 1 dimension is outside nanoscale. E.g. nanotubes, nanowires, nanorods.

2D nanomaterials: 2 dimensions are outside nanoscale. E.g. plate like shapes like graphene, nanofilms, nanolayers

3D nanomaterials: not confined to nanoscale in any dimension. E.g. dispersion of nanoparticles, multi-nanolayers etc.

6.1.2-Properties of Nanomaterials

1.**Mechanical Properties**: High strength, toughness, elasticity, and hardness
Ideal for strong, durable coatings and structures
2.**High Surface-to-Volume Ratio**: Enhanced reactivity
Useful in catalysis, sensing, and adsorption
3.**Thermal Properties**: Exceptional thermal conductivity
High thermal stability under extreme temperatures
4.**Electrical Properties**: Improved electrical conductivity:Key in electronics and energy storage devices
5.**Optical Properties& Quantum confinement effect:** If the diameter of a molecule is reduced such that it becomes comparable to the de Broglie wavelength of electron wavefunction, it experiences quantum confinement effects. The electronic as well as optical properties of such small materials considerably differ from the properties of bulk materials. **Quantum confinement causes an increase in the energy difference between energy states as well as the band gap. Both these effects strongly influence the optical and electronic properties of the materials at nanoscale.**



Applications in LEDs, solar cells, and biosensors

6. **Melting Point of Nanomaterials :**

Nanomaterials have a *lower melting point* compared to their bulk materials.
This decrease occurs because **surface atoms dominate** (high surface-to-volume ratio), causing atoms to be less tightly bound.

Nanoscale Melting Temperature

Size decreases

Surface energy increases

Melting point decreases

e.g. 3 nm CdSe nanocrystal melts at 700 K compared to bulk CdSe at 1678 K

7: Magnetic Properties

Unique magnetic behaviours: Suitable for drug delivery, magnetic separation, sensors

6.1.4-Carbon based Nanomaterials:

Graphene:

Graphene, a member of the carbon nano material family, has emerged as a wonder material that received incredible prominence within just a couple of years of its isolation from graphite Graphene involves two dimensional sp^2-hybridized carbon atom planar sheets that are tightly packed into honeycomb-like lattice.

Structure:

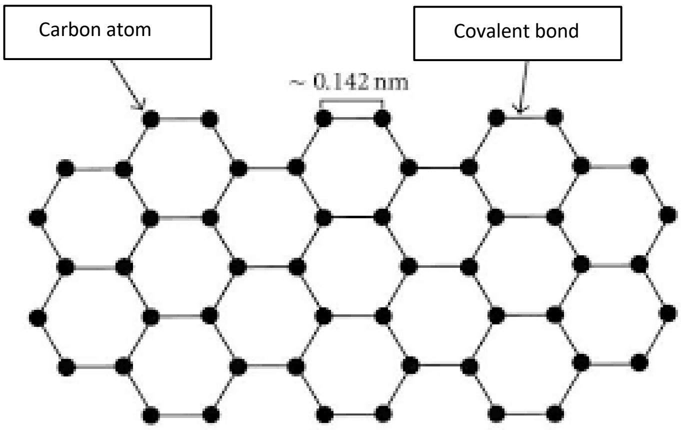
Graphene consists of a single layer of carbon atoms arranged in a hexagonal honeycomb lattice.

Each carbon atom in graphene forms three covalent bonds with its three nearest neighbours, using sp^2 hybridized orbitals.

Since each carbon atom has four valence electrons, and it only uses three for bonding, one electron remains unbonded.

These "unbonded" electrons are not confined to a single atom or bond, but rather are free to move throughout the entire sheet, forming a "pi" (π) electron cloud. *(This explains the electrical conductivity of graphene)*

The carbon-carbon bond length is approximately 1.42 Å (0.142 nm) and the graphene layer thickness is about 3.45 Å (0.345 nm).



Graphene Structure

6.1.5-Graphene: Properties & Applications

Properties	Applications
1. **Ultra-Strong** (200× stronger than steel)	**Composites & construction** for stronger, lighter materials
2. **Lightweight** (1000× lighter than paper)	**Aerospace, automotive, and portable electronics**
3. **One-Atom Thick** (Thinnest material)	**Flexible electronics** and **wearable tech**
4. **Highly Flexible** (More than rubber)	**Stretchable circuits**, **flexible displays**
5. **Transparent** (Absorbs ~2% light)	**Touchscreens**, **solar panels**, **optical devices**
6. **Excellent Conductivity** (Better than Cu/diamond)	**Faster transistors**, **supercapacitors**, **microchips**
7. **Impermeable** (To gases and liquids)	**Filtration membranes**, **protective coatings**
8. **Biocompatible**	**Drug delivery**, **biosensors**, **tissue engineering**
9. **High Surface Area**	**Sensors**, **adsorbents**, **catalyst supports**

6.2.1-Carbon Nanotubes (CNTs):

Carbon nanotubes are an essential member of the carbon nanomaterial family, and they entered the carbon family in 1991 after being discovered by S. Iijima.

Carbon nanotubes are rolled sheets of single-layered sp^2-hybridized carbon atoms (graphene), that take the shape of seamless cylinders.

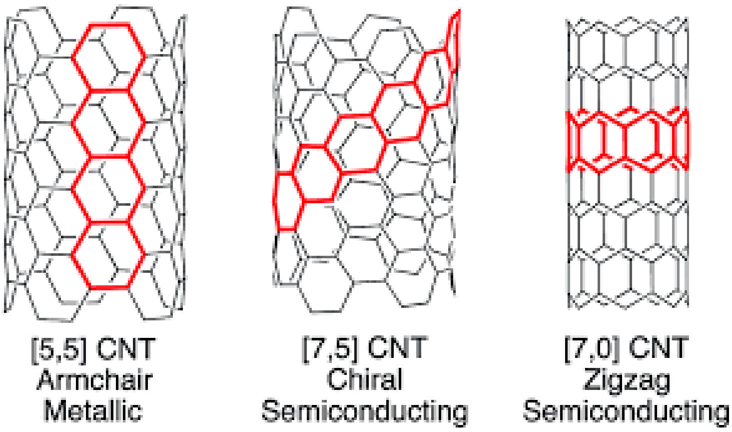
Structure:

Carbon nanotube consists of a single layer of carbon atoms arranged in a hexagonal honeycomb lattice rolled into seamless cylinder.

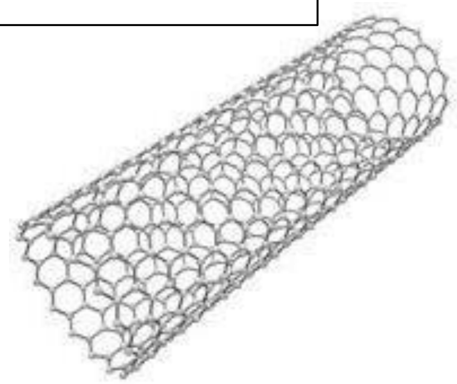
Each carbon atom in a nanotube is bonded to three other carbon atoms via strong covalent bonds, similar to the bonding in graphene.

This bonding arrangement leaves one electron per carbon atom "unbonded" or delocalized, meaning these electrons are free to move throughout the nanotube structure. *(This explains the electrical conductivity of carbon nanotubes.)*

The carbon-carbon bond length is approximately 1.42 Å (0.142 nm). The diameter of the carbon nanotubes is in the nanometre range and the length in the micrometre range.



Carbon Nanotube Structure



6.2.2-Carbon nanotubes are classified into two main types:

Single-Walled Carbon nanotubes (SWCNTs) and B. Multi-Walled Carbon nanotubes (MWCNTs)

- **Single-Walled Carbon Nanotubes (SWCNTs):**

Structure: A single layer of graphene rolled into a seamless cylinder.

Diameter: The diameter ranges from 1 to 2 nm.

Types: Carbon nanotubes are grouped into three main types based on how their atoms are arranged: **armchair**, **zigzag**, and **chiral**. These types are defined by **chirality**, which means how the carbon sheet is rolled. This affects their **angle** and **diameter**.

Electrical properties: Armchair nanotubes act like metals and conduct electricity very well. **Zigzag** and **chiral nanotubes** behave more like semiconductors, which makes them useful in electronic devices.

SWCNTs have very high **Electrical conductivity**(10^4-10^6 S/cm)

Thermal properties: SWCNTs have high Thermal **conductivity.**

SWCNTS are more flexible and have good strength (tensile strength 53 Gpa

- **Multi-Walled Carbon Nanotubes (MWCNTs):**

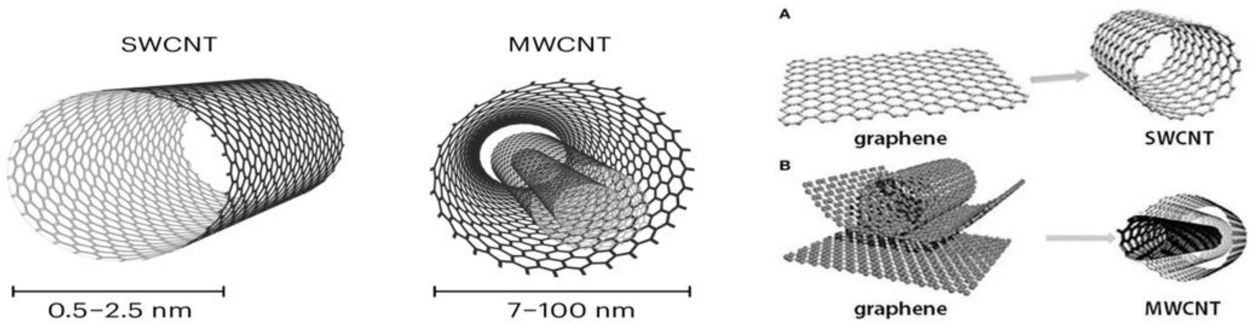
Structure: Multiple graphene layers rolled into concentric cylinders.

Diameter: The diameter can range from a 2 to 100 nm.

Interlayer spacing: MWCNTs have the distance between the concentric nanotubes typically around 0.34 nanometers.

Strength: MWCNTS are more rigid and have high strength

Structures of SWCNT and MWCNT



6.2.3-CVD for CNT Synthesis

Chemical Vapor Deposition (CVD) is a widely used method to synthesize carbon nanotubes (CNTs). It works by decomposing hydrocarbon gases over metal catalysts at high temperatures, typically ranging from 600 to 1200°C.

Process Steps

Catalyst Preparation – Metal nanoparticles (such as iron, cobalt, or nickel) are deposited on a substrate like silicon.
Introduction of Carbon Source – Hydrocarbon gases such as methane or acetylene are fed into a heated reaction chamber.
Decomposition and Growth – The gases break down, releasing carbon atoms that dissolve into the catalyst particles. These atoms then precipitate out, forming tubular CNT structures through either base-growth or tip-growth mechanisms.
Cooling and Collection – Once growth is complete, the system is cooled, and the CNTs are collected. Depending on catalyst size and reaction conditions, the process yields either single-walled (SWCNTs) or multi-walled nanotubes (MWCNTs).

Key Parameters

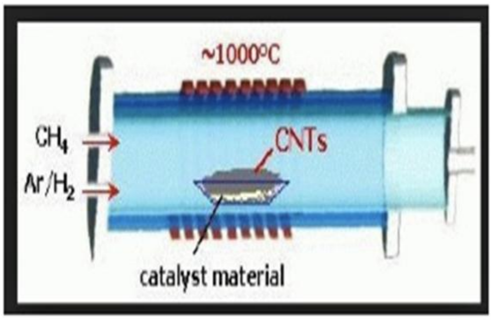
Catalyst Size – Nanoparticles smaller than ~3 nm tend to produce SWCNTs, while larger particles favor MWCNTs.
Temperature – Lower ranges (600–900°C) are suitable for MWCNTs, while higher ranges (900–1200°C) are typically required for SWCNTs.
Carbon Sources – Hydrocarbon gases such as acetylene or ethylene are common; in some cases, solid precursors can be used in cooler zones.
Substrates – Materials like silicon, quartz, or silica influence CNT yield, alignment, and overall quality.

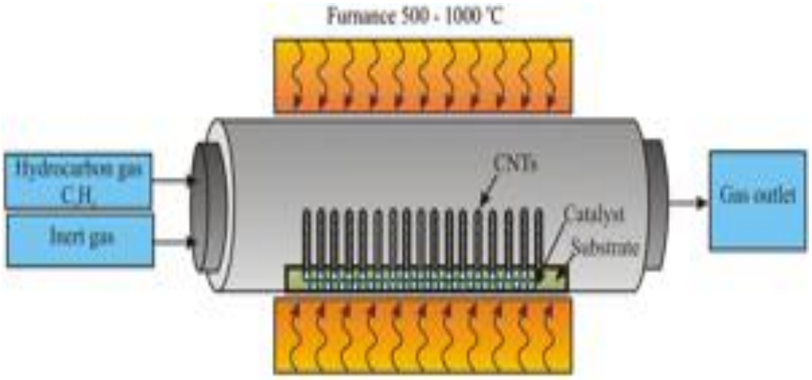
Diagram Description

A ceramic reactor tube is placed horizontally inside a furnace.

- The tube has inlets for hydrocarbon gases and carrier gases (such as hydrogen or argon), along with exhaust outlets for byproducts.
- A quartz substrate coated with catalyst nanoparticles is positioned inside the heated zone of the tube.
- Argon gas is first passed through the reactor to purge air from the system.
- The furnace is heated to about 950°C.
- High-purity reactant gases are introduced into the tube.
- Methane decomposes according to the reaction:

$$\mathrm{CH_4}(g) + \mathrm{H_2}(g) \;\rightarrow\; C(s) + 3\mathrm{H_2}(g)$$





Chemical Vapour Deposition (CVD) is a widely used technique for producing high-purity Carbon Nanotubes (CNTs) at relatively low temperatures. This method offers great versatility and efficiency, making it suitable for synthesizing both single-walled (SWCNT) and multi-walled CNTs (MWCNT). Due to its adaptability, CVD has significant industrial applications in fields such as electronics, catalysis, ceramics, and protective coatings.

6.2.4-Carbon Nanotubes (CNTs) – Properties & Applications

Property	**Application**
High Strength & Lightweight	Used in composites, automotive parts, aerospace structures, sports equipment
Excellent Electrical Conductivity	Transistors, field-emitting devices, flexible electronic displays
High Thermal Conductivity	Thermal management in electronics, heat sinks, solar cell efficiency
Chemical Stability	Corrosion-resistant materials, catalyst supports
High Surface Area	Adsorption, catalysis, gas sensors, chemical sensors
Biocompatibility	Drug delivery, biosensors, tissue engineering, cancer therapy
Semiconducting Behavior	Nanoelectronics, photovoltaic and solar energy devices
Low Thermal Expansion	Precision electronics, high-temperature applications
Electromagnetic Shielding	Protects electronic devices from electromagnetic interference (EMI)
Water Filtration Capability	Nanotube membranes for clean water, toxin and pollutant removal

Composites

6.3.1-Composites were developed because no single, homogeneous structural material could be found that had all of the desired characteristics for a given application. Fiber-reinforced composites were first developed to replace aluminium alloys, which provide high strength and fairly high stiffness at low weight but are subject to corrosion and fatigue.

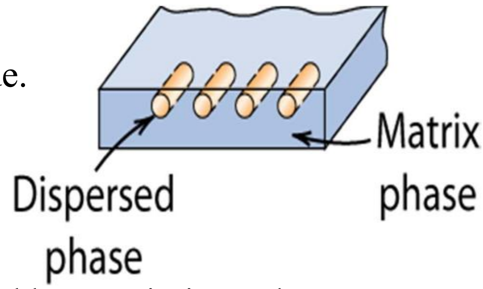
Definition:

A composite material is a material that consists of one or more discontinuous components (particles/fibres/reinforcement) that are placed in a continuous medium (matrix).In a fibre composite the matrix binds together the fibres, transfers loads between the fibres and protects them from the environment and external damage

The composite can be regarded as a combination of two or more materials that are used in combination to rectify a weakness in one material by a strength in another. A recently developed concept of composites is that the composite should not only be a combination of two materials, but the combination should have its own distinctive superior properties

Composite:

Multiphase material that is artificially made.



Phase types:

Matrix - is continuous

Dispersed - is discontinuous andsurrounded by matrix.it can be particles/fibres

Eg: **Natural composites:**

-Wood: strong & flexible cellulose fibers in stiffer lignin (surrounds the fibers).

-Bone: strong but soft collagen (protein) within hard but brittle apatite (mineral).

-Certain types of rocks can also be considered as composites

Synthetic/Manmade:

-Fiber-reinforced composites can be seen in a car tyre, where nylon or steel wires are suspended in rubber matrix.-

-Concrete : MS iron rods are used as reinforcing material with sand and gravel in the cement matrix

6.3.2-Role/Function of Matrix And Reinforcements

Matrix –

- **Binds fibers together** and maintains their position.
- **Transfers load** from the external forces to the reinforcement.
- **Protects fibers** from abrasion, moisture, and chemical attack.
- **Prevents crack propagation** due to its ductility and toughness.
- **Provides bonding** with fibers to ensure effective stress transfer.

Reinforcement -(dispersed phase)

- **Carries the major portion of applied stress** and provides strength.
- **Improves stiffness, tensile strength, and modulus** of the composite.
- **Controls crack growth** and enhances overall toughness.
- **Provides direction-specific strength** when fibers are oriented properly.
- **Enhances mechanical performance** such as fatigue, impact, and wear resistance.

Characteristics of Composite Materials

- High Strength-to-Weight Ratio: Strong but lightweight, ideal for aerospace, automotive, and structural applications.
- Excellent Durability: Long service life with good toughness, impact resistance, and fatigue resistance.
- Chemical, Weather & Corrosion Resistance: Withstand chemicals, moisture, oxidation, and harsh environmental conditions.
- Fire Performance: Modern composites offer fire-retardant and self-extinguishing properties using specialized resins/additives.
- Thermal Properties: Provide either high thermal conductivity (heat dissipation) or low conductivity (insulation); maintain strength at high temperatures.
- Low Thermal Expansion & Low Electrical Conductivity: Stable dimensionally and useful as electrical insulators.
- Design Flexibility & Aesthetic Value: Easy to mold into complex shapes; available in various finishes and colors.
- Lightweight Transparency Options & Economical: Can be made translucent (up to 85% light transmission) and cost-effective for many applications

6.3.4-Classification of Composites

(A)Matrix-based:

1)Metal Matrix Composites (MMC)

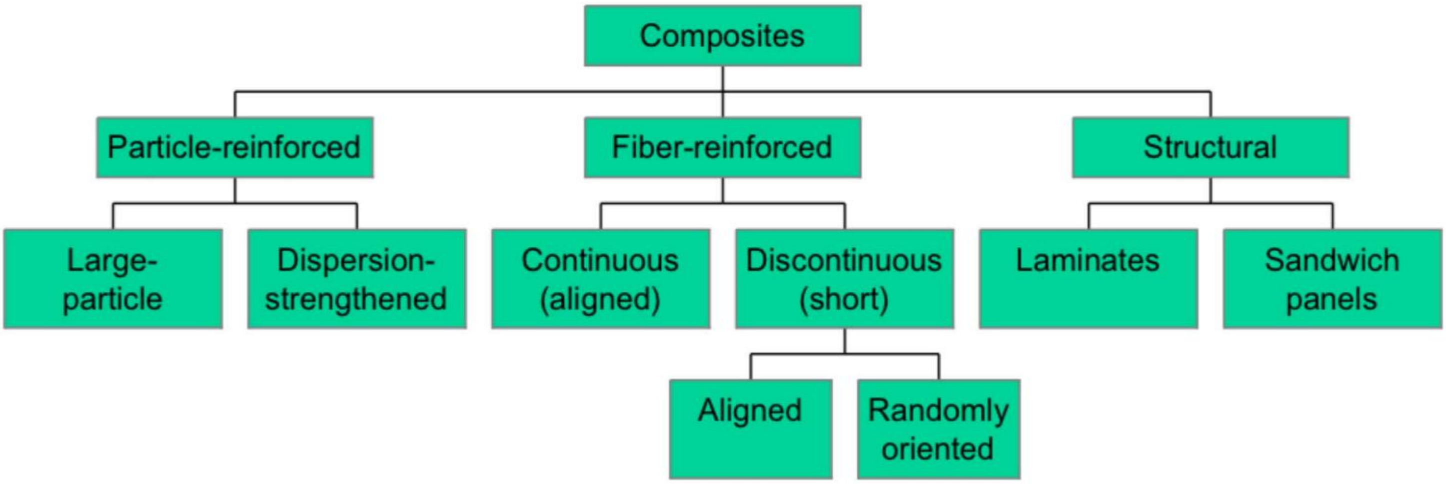
2)Ceramic Matrix Composites (CMC)

3)Polymer Matrix Composites (PMC)

Eg: Typical examples of metal matrix composites are Al - Al_2O_3 and Al-SiC.

Titanium reinforced with SiC fibres are considered for turbine blades and discs.

(B)Reinforcement-based



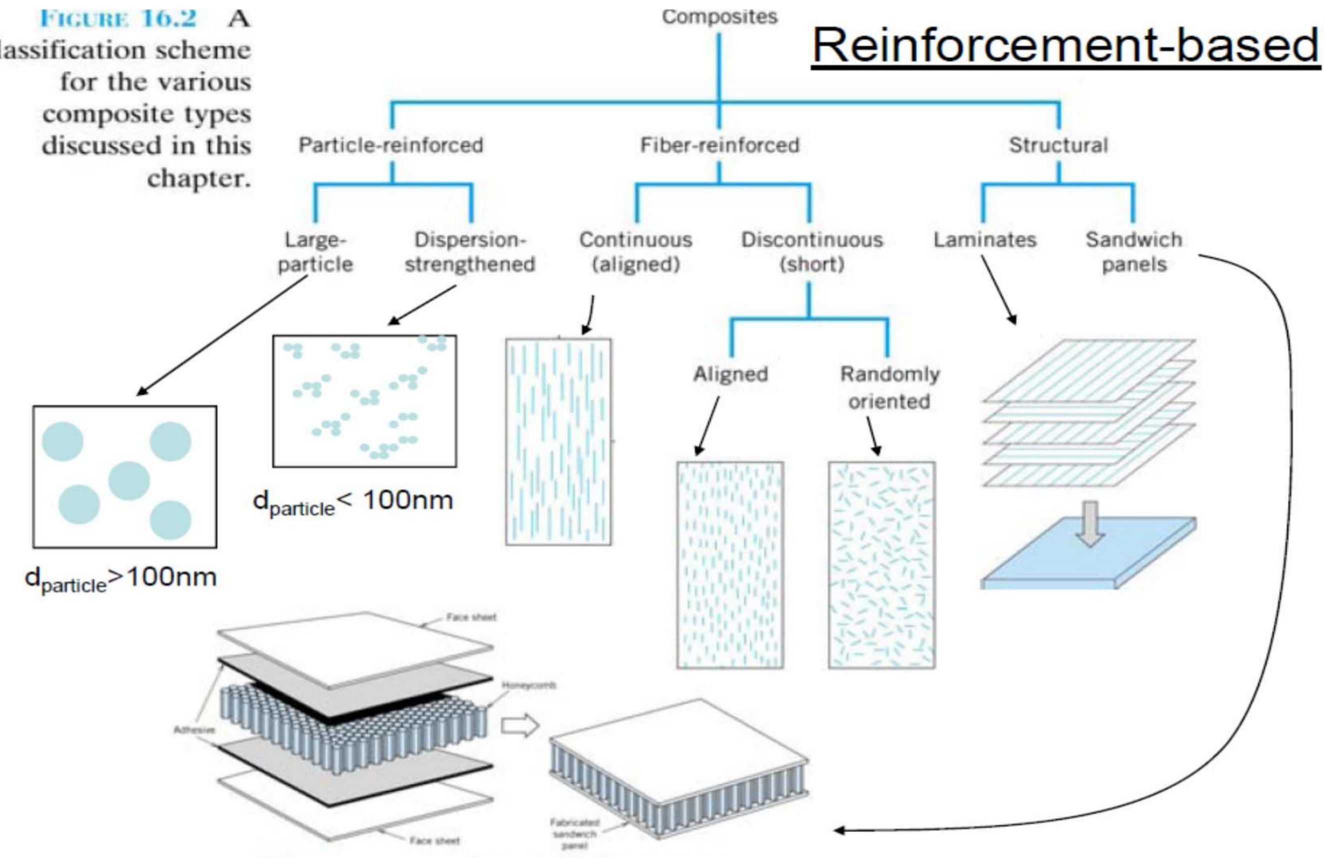
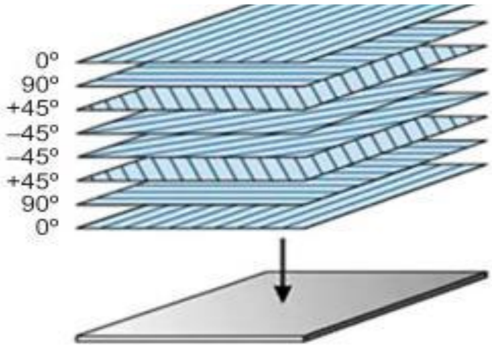


FIGURE 16.2 A classification scheme for the various composite types discussed in this chapter.

Laminates

Plywood: It is made up of several fused layers of thin wood veneers bonded with adhesive, and this procedure results in a strong, durable panel with outstanding structural integrity. The cross-grain structure, in which the wood veneers are arranged in alternating directions, gives strength to the laminated plywood and can withstand multidirectional stress.



Difference between Matrix and reinforcement:

MATRIX	REINFORCEMENT
• This constituent is continuous and in greater quantity. • Based up on matrix composite is of 3 types. PMC,CMC,MMC. • Matrix transfers the load. • It protects individual fibre from surface damage due to abrasion and oxidation. • Example: alumina, aluminium, epoxy, polyester etc.	• This may be continuous or discontinuous. • Based up on reinforcement type it can be fibre reinforced or particulate reinforced. • Reinforcement bears the load. • The reinforcing phase provides strength, stiffness. In most cases these are stronger and harder than matrix. • Example: carbon, aramid, nylon,jute etc.

6.3.5-Polymer Composites-We Will Be Focusing On Polymer Matrix Composites

Polymer Matrix Composites:Most commercially produced composites use a polymer matrix material often called a resin solution. There are many different polymers available depending upon the starting raw ingredients. There are several broad categories, each with numerous variations. The most common are known as polyester, vinyl ester, epoxy, phenolic, polyimide, polyamide, polypropylene, polyether ether ketone (PEEK), and others. The reinforcement materials are often fibers but can also be common ground minerals

Polymer Matrix Composites (PMCs)

Polymer Matrix Composites are materials made by combining a **polymer (resin)** with a **reinforcement** (usually fibers).

The polymer holds everything together, and the reinforcement gives strength.

- ✓ **Polymer Matrix (Resins)**

The matrix is usually a plastic resin. Common types are:

Polyester, Vinyl ester, Epoxy, Polyimide,Polyamide,Polypropylene amd more

These resins bind the fibers, protect them, and transfer loads.

- ✓ **Reinforcement Materials**

Reinforcement gives strength and stiffness. It can be:

- **Fibers:** glass fiber, carbon fiber, aramid fiber
- **Mineral fillers:** calcium carbonate, silica, talc

PMCs = **Polymer resin (binder) + reinforcing fibers (strength)**

Polymer Composites- Fiber Reinforced Polymer

EXAMPLES

Type of FRP	Fibers Used	Matrix	Key Features	Applications / Uses in Strengthening
1.AFRP (Aramid Fiber Reinforced Polymer)	Aramid fibers (e.g., Kevlar)	Epoxy / Polyester	- Very high tensile strength- Excellent impact resistance- Good fatigue resistance	Structural Strengthening: Strengthens concrete beams (higher load capacity) Suitable for shocks/vibrations (rail bridges, industrial zones) Good for cyclic loading (wind turbine towers) Bulletproof vests, helmets, Blast-resistant panels, Seismic strengthening of beams & columns
2.GFRP (Glass Fiber Reinforced Polymer)	Glass fibers	Epoxy / Polyester	- Cost-effective- High corrosion & chemical resistance- High tensile strength- Good impact resistance- Low density, good strength-to-weight ratio	Structural Strengthening:• Large-area strengthening (facades, retaining walls), Coastal structures, water tanks, chemical plants,Sheets, bars, grids for beams, slabs & columns, Flooring, pipes• Marine & aerospace (boat hulls, aircraft parts)
3.CFRP (Carbon Fiber Reinforced Polymer)	Carbon fibers	Epoxy resin	- Very high tensile strength- Very high stiffness- Lightweight, durable- Corrosion resistant- Excellent high-temperature performance	Strengthening bridges, high-rise columns, prestressed concrete ,Ideal for heritage structures (minimal weight addition)Other Uses:• Aerospace (wings, fuselage),Sports equipment (bikes, rods), Automotive (body panels)

6.3.6-Bio-composites: A Sustainable Alternative

A **biocomposite** is a composite material formed by a matrix (resin) and reinforcement of generally natural fibers, designed to reduce environmental impact by replacing petroleum-based, non-renewable composites.

Components of Bio composites

Matrix Phase: Formed by **polymers** derived from both **renewable** (e.g., biopolymers like PLA) and **non-renewable** sources. The matrix protects the fibers from degradation, holds them together, and transfers mechanical loads.

Reinforcement: Composed of **natural fibers** (e.g., cotton, hemp, flax, jute, kenaf) or **wood particles/fibres** from renewable sources such as recycled wood, waste paper, or crop byproducts.

ADVANTAGES: These fibers are **renewable, biodegradable**, and **recyclable**, offering significant **environmental sustainability** over synthetic fibers (glass, carbon, Kevlar).

Cost-effective: Natural fibers and bio-based matrices are often less expensive than synthetic fibers.

Environmentally friendly: Renewable, biodegradable, recyclable components, reduce ecological impact.

Mechanical Properties: Offer lightweight, strong, and durable materials for various engineering applications.

https://doi.org/10.1080/25740881.2024.2375366

6.3.7-Biocomposites- Classification Table

Type of Biocomposite	Components	Examples	Applications
1.Partial Biodegradable Biocomposites	- One component is natural / biodegradable - Other component is synthetic and non-biodegradable	- Jute/Epoxy composites - Carbon Fiber/PLA composites	Automotive: Interior panels, seat backs Construction: Insulation, roofing sheets Consumer Goods: Sustainable packaging, furniture Sports Equipment: Bicycle frames, protective gear
2.Completely Biodegradable Biocomposites	- Bio-fibers + biodegradable polymer matrices - Polymers are renewable biopolymers or petro-based biodegradable polymers	Biopolymer Matrices: - Cellulose plastics: Cellulose acetate, ethyl cellulose, cellulose sulfate - Soy plastics - Starch plastics (TPS)	Packaging: Biodegradable food containers, eco-packaging Agriculture: Plant pots, seedling trays Medical: Sutures, wound dressings

Ceramics

Engineering ceramics are a class of advanced materials vital to various technological fields due to their exceptional properties. They encompass structural ceramics, functional ceramics, and ceramic matrix composites, offering characteristics such as high-temperature resistance, wear resistance, corrosion resistance, and unique electrical, thermal, optical, and magnetic functionalities

6.4.1- Definition of Ceramics: Ceramics are inorganic, non-metallic materials formed by combining metallic and non-metallic elements, such as oxides, nitrides, and carbides. They are typically produced by shaping and firing at high temperatures. Ceramics are hard, brittle, heat-resistant, and chemically stable, existing in either a crystalline, glassy, or a combination of both forms.

Types of Ceramics:

Naturally Occurring Ceramics:

- Composed of materials like silica and alumina.

Examples: Sand, clay, gravel, and rocks

Heat-Treated Ceramics (Synthetic Type):

- Refractories: High-temperature resistant materials for industrial applications.

Examples: Acid refractories ($SiO2$), Basic refractories (MgO).

- Cement: Used for binding materials like bricks and stones.

Examples: Portland cement, slag cement.

- Abrasives: Hard materials used for cutting and grinding.

Examples: silicon carbide.

Properties of Ceramics:

- ✓ Hardness & Strength: Extremely durable with high resistance to wear.
- ✓ Heat Resistance: High melting points, making them ideal for high-temperature use.
- ✓ Electrical & Thermal Insulation: Poor electrical and thermal conductivity.
- ✓ Chemical Stability: Resistant to corrosion and most chemicals except hydrofluoric acid.
- ✓ Durability: Long-lasting and resistant to wear and oxidation.

6.4.2-Applications of Ceramics:

Refractory Materials: Used in high-temperature industrial processes like furnaces and kilns. The main function of these materials is to absorb heat from molten metal and transfer it to the surrounding atmosphere.

https://www.ganeshas.net/outstanding-refractory-materials-for-iron-steel-industry/

Primary refractories include silica sand, alumina, magnesia, zirconia, and other oxides. During smelting, molten metal produces **slag** (a waste layer). If the furnace walls melt or react with slag, the furnace gets damaged.

What do refractories do?

They withstand very high temperatures

→ So the furnace walls don't melt.

They resist chemical attack

→ Prevent slag from sticking to or corroding the furnace lining.

They absorb excess heat

→ And slowly release it into the atmosphere, keeping the furnace safe.

2.Ceramics in Aerospace

Very lightweight → Helps aircraft and spacecraft reduce weight and save fuel.

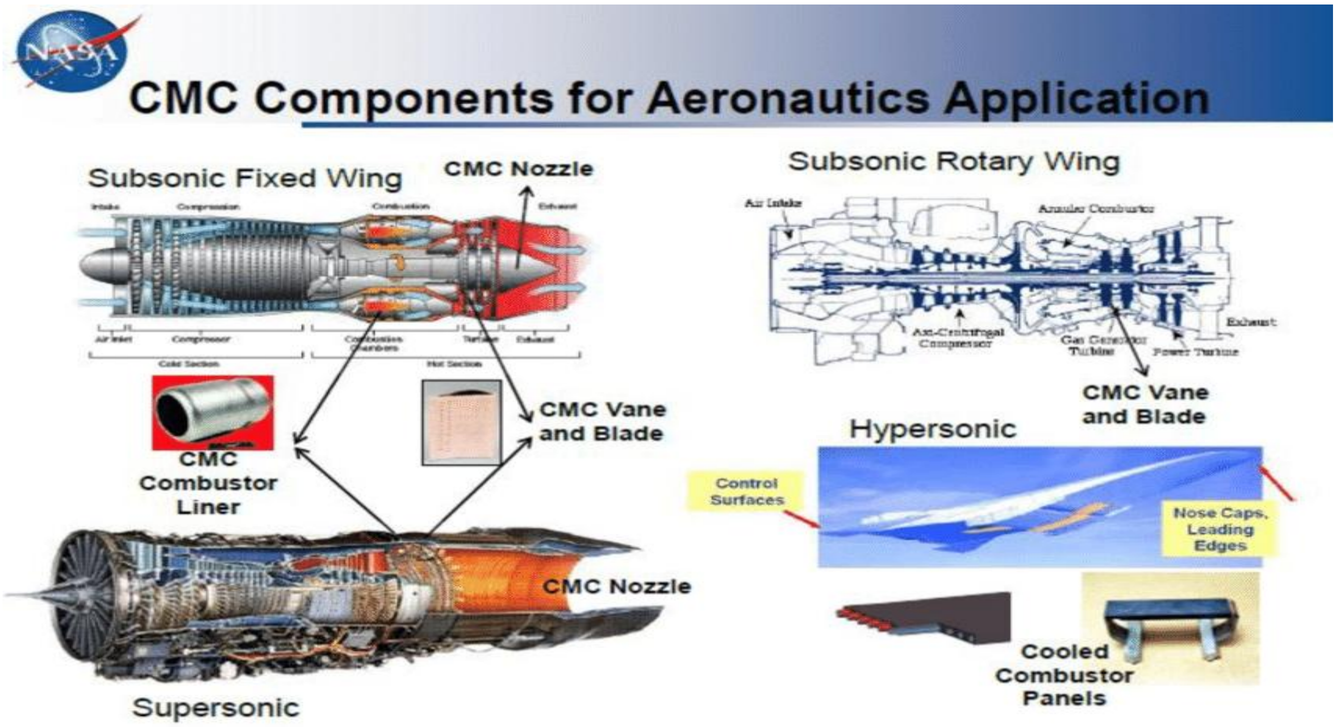
High temperature resistance → Can survive **extreme heat (2000°C+)**, especially during **re-entry** into the atmosphere.

Used in heat shields → Materials like **SiC, hafnium diboride, zirconium diboride** protect space capsules and hypersonic vehicles.

Strong and corrosion-resistant → Do not melt, rust, or weaken easily even in harsh space conditions.

Used as insulation tiles → Like those on the **Space Shuttle**, used again in modern reusable spacecraft.

Used in sensors and structural parts → Because they can handle heat and stress without deforming.



Ceramic matrix composites (CMCs) have emerged as an ideal material for high-temperature components such as aeroengine turbine blades , owing to their exceptional high temperature resistance, lightweight properties, and superior mechanical performance

Medical: Used in implants and surgical tools due to their biocompatibility-(Appendix- will be provided-student project/Assignment)

6.4.3-Overview of some common engineering ceramic materials, their properties, and applications:

Ceramic Material	**Key Properties**	**Applications**
1.Alumina (Al_2O_3)-widely used ceramic	✓ High melting point: **2050 °C**- ✓ High hardness: **1500–2000 HV**- ✓ High compressive strength: **2000–4000 MPa**- ✓ Excellent electrical insulation (**~10^{15} Ω·cm**)- ✓ Good chemical & thermal stability	-Electrical insulators, substrates- Abrasives, wear-resistant parts- Kiln furniture, chemical components- Sapphire windows & lenses
2.Zirconia (ZrO_2)-ceramic steel	✓ High toughness (transformation toughening) ✓ Flexural strength: **up to 1000 MPa**- ✓ Hardness: **11–13 GPa** ✓ Fracture toughness: **7–10 MPa·$m^{1/2}$** ✓ Low thermal conductivity: **2–3 W/m·K** ✓ High melting point: **~2700 °C**- ✓ Chemically inert & biocompatible	- Dental implants, crowns- Cutting tools, bearings- Thermal barrier coatings (aerospace)- Oxygen sensors
3.Silicon Carbide (SiC) - Hardness like diamond	✓ Very high hardness: **~2600 HV (Mohs 9.6)** ✓ High thermal conductivity: **120–200 W/m·K**- ✓ Low thermal expansion: **3.6–4.1 ×10^{-6}/K**- ✓ Strength retained up to **1600 °C**- Excellent corrosion & oxidation resistance	Furnace parts, Heat exchangers- Mechanical seals, pump parts- Semiconductor equipment- Automotive brake discs- Bulletproof armor- Abrasives: grinding wheels, sandpapers- Aerospace engine components